ABSTRACT

Title of Dissertation:	THE ROLES AND IMPLICATIONS OF AGRICULTURAL AND ENERGY RESOURCES TRADE IN A CLIMATE CHANGE-MITIGATING WORLD
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Global dependence on agricultural and energy resources trade has grown significantly in the past several decades. In the coming decades, the roles and implications of international trade of various commodities will change, influenced by and important for achieving climate mitigation goals. As globalization increases, new energy technologies emerge, and new climate-oriented trade policies are enacted, there is a need to understand the resulting implications (opportunities and vulnerabilities) on exporters and importers. I present three essays that use the Global Change Analysis Model (GCAM) to evaluate future, inter-regional trade dynamics in a climate-mitigating world.

Essay 1 focuses on Latin America and the Caribbean (LAC), a key agricultural exporting region. I show that agricultural market integration (i.e., the reduction of trade barriers) and climate mitigation policies could increase agricultural production and trade opportunities for

many LAC economies (particularly in southern South America). Total net export revenue across LAC could reach $110-$270 billion annually by 2050. However, these opportunities could also pose significant economic and environmental trade-offs, including emissions reduction challenges, potential loss of livestock production, increased consumer expenditures, and deforestation and water scarcity pressures.

Essay 2 explores the role of liquefied natural gas (LNG) trade as a rapidly emerging technology compared to pipeline natural gas. I analyze how advances in LNG technology, limitations on trade, and climate mitigation policies could affect global and regional vulnerabilities in energy supply. Globally, new additions in LNG and pipeline export infrastructure, range from 330-1330 and 130-440 million tons per annum (MTPA), respectively, by 2050 across scenarios, with the lower end of this range achieved through a transition to a net-zero energy system and limited trade. The results also highlight diverging risks for different gas exporters. For example, Russia, which produces gas largely for pipeline exports, may face larger underutilization due to advances in LNG technology and geopolitical shifts than regions oriented towards domestic and LNG markets, such as the USA and Middle East.

Essay 3 evaluates whether import-restrictions on deforestation linked oil crops (i.e., oil palm and soybean) can be effective in reducing deforestation and land use change (LUC) emissions as well as their broader economic implications. I find that current EU restrictions will likely have minimal impact. If extended beyond the EU, import restrictions could drive reductions in cumulative LUC emissions in key oil-crop exporting regions— up to 0.9% in Indonesia, 1.5% in the rest of Southeast Asia, 3.8% in Argentina and 6.7% in Brazil, relative to a scenario with no import restrictions. However, these key exporters could also face losses ranging $4.1-$61 billion in cumulative agricultural production revenue by 2050.

THE ROLES AND IMPLICATIONS OF AGRICULTURE AND ENERGY RESOURCES TRADE IN A CLIMATE CHANGE-MITIGATING WORLD

By

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What started as a side project during the summer after my first year— developing representation of natural gas pipelines and liquefied natural gas (LNG) in GCAM— became the basis of my second dissertation paper. I'm truly grateful to Dr. Gokul Iyer for bringing me into this project, which has since opened many doors to be part of crucial policy-relevant work. It was after joining this project that I decided to focus my dissertation topic on trade and climate mitigation. Gokul helped me streamline my writing to concisely bring out the most important points. Gokul also guided me in thinking deeply about my career goals as someone aiming to do policy-relevant research. I want to acknowledge funding support from GCIMS and FECM through JGCRI for supporting me as a PhD intern. Related to many aspects of the LNG work, I also want to thank Matthew Binsted for patiently answering my GCAM questions and working with me to resolve technical hurdles.

In my third year, I was lucky to have the opportunity to study abroad on UMD's Indonesia course, led by Prof. Thomas Hilde. My third dissertation paper was inspired by discussions with oil palm stakeholders and policy experts in Indonesia during this course. I became interested in similar implications of trade restrictions for oil palm exporters in Indonesia and soy exporters in Latin America, which could be relevant for the NSF Latin America project. For this third paper, I benefitted significantly from discussions with my dissertation chair, Prof. Nathan Hultman. Nate challenged me to think about what key advice I would have for policymakers, and to model scenarios that would be most relevant for them. Nate's guidance, from the prospectus to the defense, helped me hone my presentation and communication skills.

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Table of Contents

List of Tables

List of Figures

1. Introduction

1.1 Background and framing

Globalization in the past several decades has increased the magnitude of natural resources trade globally, facilitated by decreasing costs due to the information and communication technology revolution and reduction of trade barriers between countries (Anderson, 2010). The volume of global natural resource trade— including fossil fuels, agricultural and forestry products, metals, and minerals— has increased by more than 60% since 2000. Further, while global resource extraction has increased by around 1.8 times since 1980, trade in natural resources has increased by 2.5 times, implying an increasing dependence worldwide on traded commodities, especially for fossil fuels and metals, for which around half of their total production is traded (King, 2017). Recent events, including supply-chain disruptions due to COVID-19 (Falkendal et al., 2021) and Russia's invasion of Ukraine and associated economic sanctions (Pedersen et al., 2022) have contributed to lowered trade in some economic sectors and regions of the world. However, over the long-term, with continued population and economic growth, resource trade can be expected to further increase to meet increased global demands.

In the coming decades, resource trade will also be important for and influenced by climate mitigation goals, as specific commodities, trade infrastructure, and connections between regions could play key roles in facilitating the achievement of climate mitigation goals. Meanwhile global resource trade policy is increasingly becoming interlinked with climate policy, with recent examples such as the Biden Administration's recent pause on approving new liquefied natural gas (LNG) export terminals (The White House, 2024) and regulations in the EU banning the import of goods linked to deforestation (EU, 2023). As globalization increases, new technologies emerge, and new climate-oriented trade policies are enacted, there is a need to understand their roles and the resulting implications on exporters and importers.

1.1.1 The role of trade in facilitating climate mitigation actions

Resource trade could be important for achieving climate mitigation goals in several ways. Resource trade involves several components, including: the traded commodities itself, the enabling trade infrastructure to facilitate trade across regions, and the enabling institutions or policies to facilitate the integration of markets and reduction of trade barriers.

The trade of certain emerging commodities like bioenergy (Daioglou et al., 2020) or critical minerals for renewable, storage, or electric technologies (IEA, 2022) could serve key roles in transitioning to decarbonized energy systems. An increase in circular economy— the trade and use of recycled and efficient materials— can help reduce overall volumes of resource production and extend the lifetimes of existing commodities (De Sa & Korinek, 2021).

Emerging trade infrastructure, such as long-distance high voltage electricity transmission lines, could facilitate the ability to connect energy sources (e.g., distantly located wind and solar) across distances to centers of demand not previously possible, across national or even international scales (Guo et al., 2022). Similarly, liquefied natural gas (LNG) technologies offer the possibility to ship natural gas more flexibly between different sources and destinations than was previously possible through fixed pipeline networks. However, the level to which the trade of fossil fuel commodities, including natural gas, will be continued is uncertain in a world undergoing rapid decarbonization. Thus, a climate-mitigating world may also imply significant reductions of trade of certain commodities, including fossil fuels or deforestation-linked agricultural commodities.

More integration of global markets shifts production of commodities based on comparative advantages (see Section 1.1.2). The ability to produce commodities with lower emissions intensity than other producers is also a comparative advantage. Thus, integrated trade could potentially help achieve climate mitigation goals by shifting resource production, e.g., land use change-intensive agricultural commodities or energy-intensive industrial products to less-emissions intensive areas, and thus lowering global GHG emissions. Given that agricultural and energy commodity trade could take on changing roles in facilitating climate mitigation goals, it is necessary to understand the resulting implications that could result for exporting and importing regions.

1.1.2 Resulting implications (vulnerabilities and opportunities) of trade in a climate-mitigating world

Increased resource trade has inevitably benefitted some more than others and resulted in increased burdens or vulnerabilities on some more than others. In theory, based on the economic logic of comparative advantages (Deardorff, 1980), increased market integration allows countries to specialize in what they are good at producing. This would benefit producers in exporting regions by increasing their market share (and economic welfare) and consumers in importing regions, who have greater accessibility to resources and generally at cheaper prices than before. Countries increase exports of commodities that they have comparative advantages in producing, based on differences in multiple factors of production related to natural resource endowments (e.g., suitable land, water, quality of the natural resource being extracted), labor, technological productivity, and others (Costinot et al., 2016; Zhao et al., 2020). However, many of these factors have also been generated through exploitative labor practices (Burtless, 2001) or lax environmental regulations, leading to depletion or degradation of natural resources (Quiroga et al., 2007). Thus, increased trade has also created significant vulnerabilities for those producing traded commodities. As the world accelerates its climate mitigation actions, such inequitable outcomes resulting from resource trade will likely continue, as new opportunities and vulnerabilities emerge for different groups of people, in producing (exporting) and consuming (importing) regions **(Table 1-1)**.

Shifts in regional production could introduce particular risks on agricultural or energy resource producing regions. For example, increasing concentration of resource production in a few areas introduces a dual burden on these producer regions— allocating resources to produce commodities to meet ever increasing global demands, while also needing to fulfill their own climate mitigation pledges (Bataille et al., 2020; Morris et al., 2020). For example, for agricultural producers, there is a trade-off between utilizing land for increased crop production or preserving it (e.g., forestlands as a carbon sink). This trade-off is further exacerbated if demand for bioenergy, for use with carbon capture and sequestration (BECCS), as a negative emissions energy technology grows. As competition between the different uses of land— between growing agricultural crops and securing global food security, growing biomass to be used in BECCS, and afforestation increase, they will drive up agricultural prices, with resulting implications on energy and food (Fujimori et al., 2022; Hasegawa et al., 2018). Increased vulnerabilities due to the depletion of their natural resources, as well as increased challenges in being able to achieve climate mitigation goals could compound on producing regions.

Emerging trade of new technologies could also introduce significant risks for producers. For example, the mining of critical minerals often occurs in areas of mismanagement, is often acutely damaging to the local environment (e.g., depleting groundwater resources) and human health (e.g., ingestion of toxic metals), and may be a source of conflict at the sites of resource extraction (Franks et al., 2014; Sovacool et al., 2020). Increasing production and trade of bioenergy could present conflicts over scarce land by multiple users who have different goals in mind and even lead to land grabbing by large companies or foreign entities to secure its access (D'Odorico et al., 2018; Rulli et al., 2013). Global transitions to decarbonized energy sources are not likely to change the status quo on— and could in fact exacerbate— the labor, environmental, social risks that exist today.

On the other hand, the reduction of trade of certain fossil fuel or deforestation-linked commodities also has particular risks for their suppliers. This could have significant economic implications, such as underutilization and stranded assets (Binsted et al., 2020) or loss of economic livelihood for producers, which will need to be addressed. Meanwhile, if countries use trade to prolong assets that might otherwise be stranded, the ability to achieve global climate mitigation goals might be diminished (Yang et al., 2022).

Acknowledging the significant economic and environmental vulnerabilities that producing regions could face as a result of the changing trade paradigm, there are also potentially significant economic opportunities for exporters in producing essential and newly emerging commodities.

Meanwhile, the opportunities for importing regions are numerous. Importers gain access to more efficiently produced (cheaper) resources, particularly at a time when climate mitigation policies make energy and food commodities more expensive. Importers can avoid using their own potentially scarce natural resources. Importing regions can gain increased access to low-carbon technologies and have reduced vulnerabilities in energy supply due to diversification away from geopolitically concentrated fossil resources (Daioglou, et al., 2020). However, importers could also face new supply vulnerabilities if supply chains of newly traded resources (e.g., critical minerals) are highly concentrated or susceptible to geopolitical risks.

	Importers	Exporters

Opportunities	• Increased access to more efficiently produced (cheaper) commodities • Avoids resource use in importers' regions • Increased access to decarbonization technologies • Reduced fossil fuel trade lowers vulnerabilities in energy supply	• Increased economic opportunities for resource producers of essential and emerging commodities
Vulnerabilities	• New supply vulnerabilities could emerge if supply chains are geographically concentrated, or due to geopolitical reasons	• Significant environmental (and labor, health, etc.) impacts of increased resource use • Potentially increased challenges in being able to fulfill own climate mitigation pledges • Significant economic consequences on certain groups (e.g., consumer prices, stranded assets) • Increased vulnerabilities to climate-related trade policies (e.g., import restrictions)

Table 1-1. Examples of opportunities and vulnerabilities that may be experienced by importers and exporters because of the changing dynamics of trade in a climate-mitigating world.

1.1.3 The role of trade policies in a climate mitigating world

While increased trade can in theory enhance emission reductions globally, this relies on significant cooperation and coordination between countries. In the absence of global climate policies, which is the current reality, there is also significant potential for emissions leakage, which refers to the shifting of activities that produce emissions across borders, and ultimately reduces the efficacy of climate mitigation actions. Because emission reductions will not be prioritized to the same extent across countries, resource production could shift from countries with more emissions regulations (where commodities will be more expensive) to countries without these regulations.

Climate-oriented trade policies have been emerging to try to tackle emissions in disparate regions. For example, the EU has recently implemented restrictions on the import of deforestation-linked commodities (e.g., palm and soy), to induce reductions in deforestation in regions like Brazil and Indonesia. Similarly, carbon border adjustment mechanisms (CBAM), which have been proposed in some economic regions of the world (e.g., USA, EU) could help avoid some emissions leakage. CBAM policies aim to put products from foreign producers who operate without a carbon price on an even footing with products from domestic producers who do face a carbon price (Cosbey et al., 2019). However, import-side policies and CBAM cannot prevent all leakage in a world of uneven climate regulations, as producers and consumers may still choose to avoid regulated markets. Meanwhile, there are also concerns that such policies could devolve into trade protectionism, favoring domestic producers over international producers (Burney et al., 2021).

1.2 Knowledge gaps

Increased trade is often argued to be an economically efficient way to re-allocate resources from areas of abundance to areas of scarcity. For example, in literature and policy discussions, virtual water trade has often been framed as a beneficial way to meet water-scarce regions' demands while saving water globally (Chapagain et al., 2006). However, critics have argued that this view masks the considerable risks and inequities associated with trade flows, particularly for exporting regions (Allouche et al., 2015; Borras & Franco, 2011). There has been considerable literature highlighting some of these inequities historically. Emerging from the ecological economics literature, the concept of "ecologically unequal exchange" highlights the "deteriorating terms of trade" experienced by developing, exporting economies. their Many developing regions' exports are natural resources-intensive, yet their prices do not account for the environmental externalities involved, such as the amount of water consumed and/or polluted, the amount of land cleared, and GHG emissions generated. This therefore implies a "de facto transfer of wealth from poor to rich countries" (Falconí et al., 2017). Numerous empirical studies have highlighted ecologically unequal exchange historically, (e.g., Jorgenson, 2009, Austin, 2010, Oki et al., 2017; Hong et al., 2022).

However, there has been insufficient evaluation of the potential ***future*** impacts that regions and sub-regions could face as a result of increased trade, in particular, as the world takes on more stringent climate mitigation actions. There has not been sufficient evaluation of how increased trade intersects with climate mitigation actions, in reshaping energy and agricultural trade flows, changing sectoral emissions mitigation burden and affecting the ability to reach climate goals, and the resulting impacts on economic welfare (e.g., food security for consumers, underutilization of infrastructure), and environmental impacts (e.g., land and water systems).

Moreover, as new technologies emerge and new climate-oriented trade policies are deployed, in support of or alongside global climate mitigation actions, it is important to understand their role in the above.

1.3 Research questions and study approach

The overarching question this dissertation seeks to address is: *"What are the roles and implications of agricultural and energy resource trade in a climate change mitigating world"?* As discussed in Section 1.1, there are several dimensions that may potentially impact the future evolution of resource trade, as the world undertakes significant climate mitigation ambition. These include, for example:

- The degree to which global markets become integrated (i.e., trade barriers are lowered)
- The emergence of newly traded commodities or infrastructure by which to trade commodities
- The existence of climate-related trade policies which reshape trade patterns

Each of these dimensions are addressed in the essays that constitute the dissertation. It is not possible to comprehensively evaluate the roles and implications of all types of agricultural and energy resource trade in all regions, in order to answer my broad question, and therefore I narrow the focus, in terms of geographical scope and traded commodity type(s) in each essay (see **Table 1-2**).

To address the insufficient evaluation of potential future vulnerabilities that different regions (in particular, exporting regions) may face resulting from increased trade and climate mitigation policies, Essay 1 is focused on the future evolution of agricultural production and trade in Latin America and the Caribbean. LAC is a region that plays key roles in both meeting global agricultural demands and maintaining carbon sinks due to its abundant land and water resources. This essay asks the following question:

- How might faster integration of global markets and land-based climate mitigation policies affect agricultural trade opportunities and resulting vulnerabilities across LAC?

Essay 2 addresses the future evolution of a key-emerging trade infrastructure technology, liquefied natural gas (LNG), as distinct from the traditional means of natural gas trade through pipelines, particularly as the world transitions to low-carbon energy systems. As a lower-carbon (compared to coal), but not zero-carbon fuel, the role of natural gas trade in a decarbonizing world is uncertain. This essay asks the following question:

- How might advances in LNG technology, trade limitations, and faster transitions to low-carbon energy systems affect global and regional vulnerabilities in energy supply and trade capacity additions and underutilization?

Essay 3 evaluates the impacts of a particular climate-oriented trade policy recently implemented by the EU, import bans on deforestation-linked oil crops, as well as its potential to help achieve climate mitigation goals. This essay asks the following questions:

- How might oil crop import restrictions contribute to reducing deforestation and LUC emissions?
- What are the resulting economic implications of such bans?

	Geographical scope	**Traded commodity types focused on**
Essay 1	Regional to sub-regional; within LAC	Agricultural (crops and livestock)
Essay 2	Global to regional	Natural gas (pipeline and LNG)
Essay 3	Global to regional	Deforestation-linked oil crops (palm oil and soybean)

Table 1-2. Units of analysis for each of the three essays.

1.4 Research methodology

1.4.1 Global Change Analysis Model

All three essays use the Global Change Analysis Model (GCAM). GCAM is detailed-process integrated assessment model (IAM) (Fisher-Vanden & Weyant, 2020; Weyant, 2017) that has been developed over decades (Calvin et al., 2019). Detailed process IAMs developed out of a need to understand the energy-economy impacts of climate mitigation policies, and later evolved to represent interactions between multiple, interconnected sectors (Weyant et al., 2017). However, historically, IAMs have not been used to study issues related to global commodity trade. GCAM covers the interactions between socio-economic, energy, land, water, and climate systems globally in response to human and earth system drivers. GCAM has been used in major studies assessing climate mitigation pathways (e.g., Fawcett et al., 2015; Ou et al., 2021) and has also been used recently to explore future implications of trade (e.g., Zhao et al., 2021, 2022; Graham et al., 2023).

Many different types of models could be used (and have been to study similar questions). These include detailed models representing trade in one particular sector (e.g., gas trade models; Egging et al., 2019) or computable general equilibrium models, which include strong representation of trade across economic sectors, but not necessarily linked to physical sectors, including land, climate, and water, which commodity trade affects (e.g., GTAP; Villoria et al., 2022).

The benefits of GCAM lie in its inter-regional and inter-sectoral coverage and its connection between physical commodity trade and impacts on sectors. For the questions asked in each essay of this dissertation, it is important to have a global model that includes inter-regional trade dynamics, to have competition between multiple technologies in meeting multiple, endogenous demands, and to be able to evaluate multiple sectoral impacts (e.g., economic, land and water use, and emissions). Because GCAM represents all these aspects, it is an appropriate and beneficial model to use.

1.4.2 Approaches to modeling trade

How trade can be represented in an IAM

	"HOV" fully integrated global markets	"Armington" global pool trade	"Armington" regional pool trade	Bilateral trade
Description	Single global market for all commodities	Single global market for all traded commodities, differentiated from domestic commodities	Regional markets for traded commodities	Bilateral markets for traded commodities (region imports directly from an exporter)
Example in GCAM (Documenting study)	GCAM v5.2 and prior for all agriculture and energy commodities	GCAM v5.3+ for most agriculture and energy commodities (Zhao et al., 2022)	GCAM 7 for pipeline natural gas, traded in 6 regional pools (Yarlagadda et al., 2024)	(Yarlagadda et al., *submitted)* for oil palm and soybean markets
Examples in other IAMs	All agricultural commodities in IMPACT, MAgPIE, GLOBIOM	All energy commodities in REMIND and WITCH; most fuels in MESSAGE All agricultural commodities in AIM		Pipeline natural gas in MESSAGE, all energy commodities in TIAM-ECN, IMAGE All agricultural commodities in MAGNET, ENVISAGE, GTEM, FARM, EPPA, GTAP
Strengths	May be realistic in the very long term as globalization reduces trade barriers between regions	Middle of the road approach. Can calibrate regions' import/export status without being tied to specific trade partners. May be realistic for some commodities like oil.	Realistic for the trade of certain commodities which are limited by geographical scale, for example.	Realistic in the near term, reflecting actual trade relationships between regions. Allows for differentiation of commodities (e.g. water or emissions intensity) based on source or destination.
Drawbacks	Not realistic in the near term. Lacks detail about regional trade relationships (who's trading with who?). Does not allow for regional price differentiation.	Not realistic in the near term for most commodities. Lacks detail about regional trade relationships (who's trading with who?)		Bilateral trade calibrations in the base year won't account for new/changing trade relationships between regions.

2100 ← 2015
Increasing global market integration over time on crops
(Zhao et al., 2021)

Figure 1-1. How trade can be represented in IAMs. Four main approaches (HOV fully integrated global markets, Armington global pool trade, Armington regional pool trade, and Bilateral trade) are described in the columns. The approach of increasing global market integration over time is shown as an arrow moving from Armington global pool trade towards HOV fully integrated global markets over time, as it simulates moving in this direction over time.

There are many possible ways to model resource trade in IAMs **(Figure 1-1).** No single approach is perfect in representing both present and future real-world trade dynamics.

On one end, Heckscher-Ohlin-Vanek (HOV) assumptions of a single global market and price with no differentiation between domestic and international commodities (Bekkers et al., 2020) are highly simplified and do not represent how most commodities are traded. HOV assumptions lack detail about regional trade relationships and do not allow for regional price differentiation. However, most commodities are increasing in their globalized nature, with some commodities, like oil already traded at a single global price. HOV may be reasonable in representing trade flows in the very long-term when it is uncertain how much historical trade relationships or trade barriers persist.

On the other end, bilateral trade represents the true geography of traded flows as they exist currently and in near term. This could be realistic in the near term in reflecting actual trade relationships between regions. A bilateral trade approach allows for the differentiation of commodities based on source or destination, which is helpful in tracking differences in production (land, water, emissions intensity) by source. However, calibrating to historical bilateral trade relationships assumes that, in the absence of any intervention, bilateral trade flows will be similar to those in the past, which is not always the case as new players enter the market.

Finally, Armington assumptions are a middle-of-the-road approach. Armington approaches represent gross trade using a single, global market (or regional pools) for imported commodities (Bekkers et al., 2020). Under an Armington approach, trade is calibrated to a regions' preference for domestic vs. imported commodities, but a region is not tied to any given existing bilateral trade relationship. However, like HOV, Armington assumptions lack detail about regional trade relationships (i.e., who's trading with whom?).

In summary, bilateral trade structure could be more accurate in representing near-term trade behavior, while HOV is better for representing very long-term behavior, and Armington is somewhere in the middle. A "market integration" approach bridges the benefits in near vs. long term by allowing markets to become more globally integrated over time.

Across the three essays, I use different trade approaches (see **Table 1-2**). Essay 1 uses Armington assumptions with a single, global market for all agricultural commodities, and introduces market integration parameters to reduce preferences for domestic vs. imported commodities over time. In evaluating the role that Latin America may play in the coming decades as a key agricultural exporting region, increased market integration over time is a key dimension that could affect this role. Essay 2 uses Armington approaches with a single global market for most energy commodities, including LNG and has regional markets for pipeline natural gas. This differentiation reflects the differences in how pipeline natural gas versus LNG may be traded; while pipeline gas is limited by its physical infrastructure to the continental scale, LNG can be flexibly shipped between regions globally. Essay 3 uses bilateral trade for oil palm and soy and Armington gross global trade for all other agricultural commodities. Using a bilateral structure here allows us to differentiate oil crop exports that come from deforesting versus afforesting regions, and track which specific regions import these crops, which is relevant in representing import restrictions.

1.5 Dissertation outline

The rest of this dissertation is structured as follows. The next three chapters (Chapters 2-4) are the three essays that comprise this dissertation. Chapter 5 concludes by summarizing the key findings of this dissertation, its contributions (research, methodological, and policy), and outlines some directions for further research.

2. Essay 1: Trade and climate mitigation interactions create agro-economic opportunities with social and environmental trade-offs in Latin America and the Caribbean

This essay is based on: Yarlagadda, B., T. Wild, X. Zhao, L. Clarke, R. Cui, Z. Khan, A. Birnbaum, and J. Lamontagne (2023). Trade and Climate Mitigation Interactions Create Agro-Economic Opportunities with Social and Environmental Trade-offs in Latin America and the Caribbean. *Earth's Future.* https://doi.org/10.1029/2022EF003063

2.1 Introduction

Latin America and the Caribbean (LAC) is a major agricultural exporting region and is likely to maintain this pivotal role in the coming decades (CELAC et al., 2016; Morris et al., 2020). The region supplies the world with large fractions of several notable commodities; for example, LAC exported 91 million tonnes (Mt) of soybeans (59% of world exports), 22 Mt of raw sugar (62%), 4.2 Mt of coffee (52%) and 2.9 Mt of beef products (38%) in 2019 (FAOSTAT, 2022). Major agricultural exporters include Brazil, Argentina, Mexico, and Chile (Morris et al., 2020, Willaarts et al., 2014). It is critical to understand the nature of future agricultural production and trade opportunities that will emerge across the region, because those opportunities will directly affect societal objectives such as economic growth and sustainable development. Agriculture currently accounts for more than 5% of GDP in twenty LAC countries, and contributes to economic growth and diversification, employment, poverty reduction, food security, and ecosystem services (Morris et al., 2020). How agricultural production and trade dynamics unfold in LAC also has implications far beyond the region. International agricultural trade originating from LAC represents a large and growing source of global supply-chain risk, with the potential to create complex and far-reaching food, energy, and water security risks (Taherzadeh et al., 2021).

Despite its importance, the scale of future agricultural production and trade opportunities in LAC is not well understood. Numerous forces, both within and outside LAC, could shape these opportunities, as well as their economic and environmental consequences across the region. For example, technological change in agriculture and socio-economic growth may greatly increase the supply of and demand for agricultural commodities produced in LAC, respectively. Here, we focus on the possible effects of future variation in two global-scale drivers: increasing global integration of agricultural markets and land-based climate mitigation measures. Individually and together, these two drivers have the potential to greatly shift agricultural production and trade patterns globally and result in complex multi-sectoral impacts across LAC.

Long-term trends such as globalization and the lowering of market barriers and trade costs have grown the value of global agricultural trade more than seven-fold in the last three decades (Zhao et al., 2021, 2022). Future agricultural production and trade dynamics will be influenced by the extent to which these trends continue. In general, regions will increase exports of commodities that they have comparative advantages in producing. Agricultural comparative advantages are determined by relative productivity differences in multiple factors of production related to natural resource endowments, labor and technology productivity, and others (Costinot et al., 2016; Zhao et al., 2020). LAC, which has the largest agricultural land and water availability per capita in the world, could have significant economic opportunities from increased trade liberalization in agricultural markets (Flachsbarth et al., 2015, Willaarts et al., 2014).

Land-based climate mitigation strategies may also be prominently influential in affecting future agro-economic, land, and water use outcomes, as demonstrated by previous studies of key global drivers of change (e.g., Dolan et al., 2021, 2022). Indeed, efforts to limit global warming to less than 2°C will require unprecedented changes across sectors (IPCC, 2022). Attaining climate goals relies on comprehensive climate mitigation policies covering all greenhouse gas (GHG) emissions (Ou et al., 2021), including policies that reduce emissions in the agricultural sector. Such policies may require significant changes in the production and consumption of crops and livestock, which could have important implications for sub-regions within LAC. For example, purpose-grown biomass for energy or afforestation could compete directly for land with food crops within the region, or indirectly by inducing higher crop production to serve other regions facing land competition (Fujimori et al., 2022; Hasegawa et al., 2021). LAC is the world's largest producer of ecosystem services through its vast forest and savannah lands yet pursuing both increased agricultural production and afforestation could pose trade-offs with one another (Morris et al., 2020; Bataille et al., 2020). Meanwhile, changes in livestock management practices may be needed to reduce livestock non-CO_2 emissions. For LAC in particular, there is a large potential for GHG emissions reductions from the livestock sector, given the current dominance of land- and emissions-intensive grazing production systems (Congio et al., 2021; Frank et al., 2019; Havlík et al., 2014; Herrero et al., 2016). Thus, climate mitigation policy may be as influential as agricultural market integration in shaping the future of agricultural production and trade in LAC.

Comprehensively assessing agricultural trade opportunities in LAC, and how they may be influenced by complex combinations of global forces, requires acknowledging the region's heterogeneity and conducting a nuanced assessment of how opportunities and challenges may emerge across the region's countries, water basins, sectors, and groups within society. For example, heterogeneity in the region's natural resource endowments could lead to starkly different water and land scarcity outcomes across the region stemming from increased agricultural production and trade. Likewise, there could be disparate impacts on people with different income levels and facing different levels of food insecurity. For example, though the prevalence of undernourishment across LAC was 7.3% in 2018, the Caribbean had much higher levels of undernourishment at 17% in 2018 (FAO et al., 2020). Holistically understanding the effects of future agricultural market integration and mitigation policy on societally relevant outcomes in countries, water basins, sectors, and groups within society in LAC is currently a gap in the literature. Better understanding of these potential impacts could inform more balanced regional planning (e.g., investments from multi-lateral development banks), and could guide national and sub-national policymaking discussions surrounding how to achieve balanced progress across multiple societal goals, including agro-economic development and climate mitigation.

2.1.1 Literature review

Previous studies considering different global agricultural trade regimes have largely focused on the benefits that increased trade could achieve globally due to more efficient allocation of production and reduced cropland use and land use change (LUC) emissions (Zhao et al., 2022). Much literature has focused on interactions between climate change impacts and global market integration, highlighting the role that trade can play in helping alleviate worsening outcomes from climate impacts on agriculture (Baldos & Hertel, 2015; Brown et al., 2017; Huang et al., 2011; Janssens et al., 2020; Zimmermann et al., 2018). LAC, as a region that may have relatively minimal changes in agricultural yields due to climate change (Janssens et al., 2020), could face even higher global agricultural demands from other regions that face declining agricultural yields.

However, previous studies have generally not considered the interactions of trade integration with climate mitigation policies in the agricultural sector. In addition, few studies have evaluated future regional impacts, such as the social and environmental trade-offs that could emerge from increased agricultural trade in the coming decades, particularly in export-dominant regions like LAC. Historically, LAC has been the second largest deforestation hotspot in the word, making way for increased agricultural areas (Willaarts et al., 2014). Hong et al. (2022) showed that agrarian regions in the southern hemisphere (including LAC) have been responsible for the largest share of land-use emissions embodied in exported commodities, often resulting from deforestation. Studies have highlighted the "deterioration of terms of trade" that LAC has been experiencing in the last several decades, because the region has been increasingly supplying global food demands at lower market prices, yet it bears significant environmental costs that are not accounted for (Cango et al., 2023; Falconí et al., 2017). Flachsbarth et al. (2015) highlighted potential future environmental trade-offs in LAC from increased trade liberalization, including worsening water quality, increased LUC emissions, or biodiversity loss.

2.1.2 Research questions

Detailed-process integrated assessment models (IAMs) that capture the interconnections between sectors and regions at a global scale are well suited to analyze the long-term (e.g., mid-century) impacts of market integration and climate mitigation (Fisher-Vanden & Weyant, 2020; Weyant, 2017). Here, we use an IAM to analyze the effects of differing levels of these global drivers on agricultural production and trade in LAC, as well as consequences for agricultural producers, agricultural consumers, and integrated land-water-climate systems across LAC through mid-century. Our study is aimed at answering the following key questions. First, what might LAC's future role be in supplying global agricultural demands and in reducing GHG emissions? Second, how might the future evolution of two global-scale drivers, global market integration and climate mitigation, alter agricultural production and trade prospects across LAC's economies? Third, as LAC navigates agricultural production and trade opportunities, how might the benefits and challenges be distributed across the region's water-economy regions (WERs), land and water sectors, and groups within society?

2.2 Methodology

2.2.1 GCAM assumptions

In this study, we use a modified version of GCAM v5.4, hereafter referred to as GCAM-LAC. GCAM-LAC has been used in several studies previously to explore LAC energy-water-land dynamics under global change (e.g., Delgado et al., 2020; Khan et al., 2020; Santos da Silva et al., 2021; Wild, Khan, Clarke, et al., 2021; Wild, Khan, Zhao, et al., 2021), and we retain several input files from these studies to improve the fidelity of energy-water-land projections in LAC. GCAM-LAC is calibrated to a 2015 base year and solves for commodity prices such that supply and demand are equal across all energy, agriculture, and water markets at five-year time steps through 2100.

In GCAM-LAC, the world is disaggregated into 33 economic regions, the resolution at which socioeconomics, energy, and market processes (including global trade) are modeled, as well as 235 large water basins, the resolution at which water supply-demand balances are met. The intersection of the economic regions and water basins, hereafter referred to as water-economy regions (WERs), forms the resolution at which land-use (i.e., agricultural production) decisions are made. Out of these regional delineations, 8 economic regions, 42 water basins, and 61 WERs fall within LAC **(Figure 2-1)**. In this study, we employ several units of analysis, first considering LAC as an aggregated region in comparison to the rest of the world (ROW), next considering each of the 8 economic regions within LAC, and finally telescoping into finer resolution across LAC's WERs.

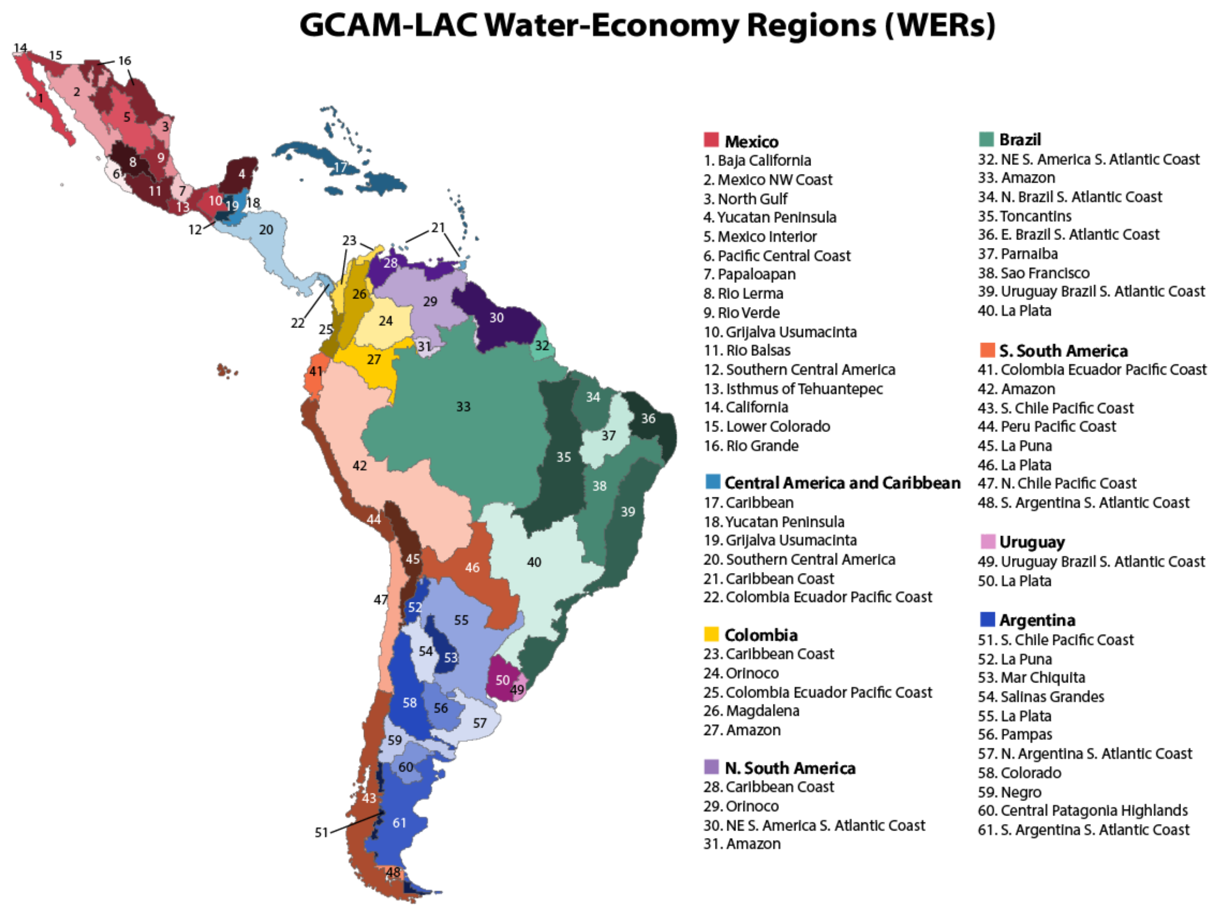

Figure 2-1. GCAM-LAC Water-Economy Regions (WERs). Note that WERs are defined as the intersection of economic regions and water basins. Colors correspond to the 8 GCAM economic regions in Latin America and the Caribbean (LAC), and shades of these colors are used to delineate the 61 WERs within these 8 regions. **Table A-1** details countries in each of the 8 GCAM-LAC economic regions.

This study focuses on impacts on water and land systems across LAC, so we provide additional details here about the representation of these subsystems in GCAM. Land is allocated to commercial and non-commercial uses of pasture, forest, and crops based on a logit model of sharing of the relative profitability of the land for different competing uses. By default, GCAM assumes that 90% of all non-commercial land area is protected and therefore any land expansion or contraction will not affect this area. GCAM allows for agricultural production of several crop and livestock commodity categories (see **Table A1-2** for details) aggregated from FAO data.

Global agricultural trade is modeled with the Armington approach, in which each economic region consumes agricultural commodities from a mix of domestic and imported supplies (which are imported from a single, global market). This approach implies that there is a differentiation between domestic and imported products. Preference bias in the Armington approach broadly represents unmeasured trade barriers and costs (e.g., non-tariff barriers, imperfect information). The preference parameters are parametrized and calibrated to base year trade flows and prices for each region and commodity (Zhao et al., 2021, 2022). As a default, these preferences, usually favoring domestic products, remain fixed over all future model periods.

Crop commodities are differentiated by water usage characteristics (irrigated versus rainfed) and management practices (high-yield versus low-yield, implying different fertilizer requirements). Water serves as one of several priced inputs that can alter irrigated crop profitability. Water is demanded in six sectors (irrigation, livestock, primary energy production, electricity generation, industrial and municipal demands), driven by bottom-up estimates of water as a requirement to productivity in those sectors (e.g., the water required to satisfy biophysical requirements for crop growth for different crop types and to compensate for irrigation inefficiency losses). Thus, when allocating water to either irrigated or rainfed crops, the model considers the water availability in the basin as well as water demands from all competing sectors. To meet water demands, water can be supplied via desalination, non-renewable (i.e., fossil) groundwater, and renewable surface water (i.e., runoff). Each of these water sources has its own supply cost curve, which have been documented across a suite of previous studies (see Appendix Text A.1 for details).

2.2.2 Scenario details

To answer our key questions, we develop and explore four stylized scenarios consisting of variation along two dimensions of global change: global agricultural market integration and land-based climate mitigation policy **(**see core scenarios in **Table 2-1** and additional sensitivity scenarios in **Table A-3)**. The market integration dimension explores the reduction of trade barriers in agricultural markets over time, while the climate mitigation dimension explores the implications of deep emissions reductions across energy and land use sectors.

		Global market integration	
		Fixed historical preferences between domestic vs. international commodities	***Global integration of markets over time***
Climate mitigation policy	***No policy***	Reference (REF)	Market Integration (MI)
	GHG policy (includes mitigation of CO_2 and Non-CO_2 emissions) in energy and land sectors	Climate Mitigation (CM)	Market Integration + Climate Mitigation (MI + CM)

Table 2-1. Scenario design.

Our stylized scenarios **(Table 2-1)** are intended to represent plausible upper and lower bounds in global market integration and land-based climate mitigation measures. These scenarios are not intended to represent 'likely' outcomes. Rather, the scenarios are a useful means of exploring the possible range of future relative and combined implications of two key dimensions of global change for agro-economic and environmental outcomes across LAC.

Along the global market integration dimension, our reference (REF) scenario includes the default GCAM agricultural trade representation, as described above, in which regions maintain historical preferences between domestic and imported agricultural commodities through 2050. In contrast, in the market integration (MI) scenario, regions gradually reduce preference bias for domestic versus imported agricultural products, moving towards unconstrained global free trade. Our MI scenario uses the high home bias erosion parameters from Zhao et al. (2021), in which agricultural markets are more globalized compared to historical average conditions, as a result of easing trade barriers. In MI, global markets take 17 years to become 50% more integrated compared to 2015 levels, in contrast to taking 45 years to reach this level in the REF scenario. Thus, in 2050, global markets would be about 75% more integrated relative to 2015 levels in the MI scenario, compared to 42% more integrated in the REF scenario. See SI Text S2.1 for additional details. Zhao et al. (2021) previously implemented market integration only on crop commodities, whereas here we apply constant (REF) and increasing (MI) levels of market integration on both crop and livestock markets, because both have important implications for economic and environmental outcomes in LAC.

Along the climate mitigation dimension, our REF scenario includes no climate policy, while our climate mitigation (CM) scenario includes several components to comprehensively cover both CO_2 and non-CO_2 emissions reductions in the energy and land sectors (see Appendix Text A.2 for details). Our climate mitigation measures take effect in 2025 and ramp up through 2050. We impose a linear constraint to achieve a 90% reduction in CO_2 for nine regions by 2050: each of the 8 LAC regions and rest-of-world (ROW). This simulates a level of ambition consistent with achieving net-zero CO_2 emissions shortly after mid-century. We price LUC CO_2 emissions at 10% of the level applied to fossil fuel and industrial (FFI) CO_2, consistent with previous studies (Feijoo et al., 2019). The resulting global CO_2 emissions pathway results in less than 700 $GtCO_2$ of cumulative CO_2 emissions by 2050 and is consistent with limiting end-of-century temperature increase to well below 2°C **(Figure A-1;** Huppmann et al., 2019**)**.

We apply the corresponding ROW CO_2 price to all non-CO_2 GHGs (**Figure A-2)** for all 8 LAC regions and ROW, to have mitigation action taken on non-CO_2 emissions. Non-CO_2 emissions represent a large fraction of GHG emissions in LAC **(Figure 2c).** Non-CO_2 emissions reductions are based on assumed marginal abatement cost (MAC) curves for each region and technology, representing the level of emissions that will be reduced at any non-CO_2 price (see Appendix Text A.2 for details). In the CM scenario, we apply the USA livestock MAC curves to all regions to represent technological improvements in Latin American production; this assumption is contrasted with each region utilizing differentiated livestock MAC curves (GCAM defaults) in a sensitivity scenario, "CM (diff. MAC)" (**Table A-3**). Price transmission is endogenously considered in the model, thus as GHG prices are levied, costs propagate through the system, increasing agricultural commodity prices. In order to avoid large-scale deployment of bioenergy with carbon capture and sequestration, which could have negative impacts on several planetary boundaries (Heck et al., 2018), we set a global constraint of 100 EJ on first- and second-generation biomass, consistent with deployment levels assumed in AR5 WGIII report (IPCC, 2014).

2.3 Results

In the Results subsections to follow, we evaluate several economic and environmental metrics at LAC-wide, economic region, and sub-regional (water-economy region) scales (**Table**

A-4). Details on metric calculations are provided in Appendix section A.3. All maps were generated using the rmap package (Khan et al., 2022).

2.3.1 LAC's role in supplying global agricultural and climate needs

In this section, we answer the first research question by analyzing how agricultural production and trade may evolve in LAC as a whole. We then demonstrate LAC's potential role in affecting global GHG emissions, and we identify trade-offs that exist between agro-economic and climate mitigation goals. In the following sections (2.3.2 and 2.3.3), we delve into the regional and sub-regional implications of each scenario (and their combinations).

Globally, our results show that agricultural production and trade revenue increase over the coming decades to meet increasing overall demand **(Figure 2-2)**. The total global value of agricultural production increases by 57% (from 2015 to 2050) in our REF scenario. In our MI scenario, global trade grows at an average of 4.8% annually (double the rate of global GDP growth), and the value of global agricultural production increases by 70% from 2015 levels by 2050.

In LAC, many sub-regions have abundant land and water resources **(Figures S3 and S4)** and high agricultural productivity, so increases in agricultural market integration could present a significant economic opportunity. By 2050, agricultural production revenue in LAC increases by 61% and 98% from 2015 levels, reaching \$770 and \$950 billion of annual revenue, under REF and MI scenarios, respectively **(Figure 2-2a)**. Annual net export revenue from LAC increases to 107% and 412% over 2015 levels, reaching \$110 and \$270 billion in 2050, in the REF and MI scenarios, respectively **(Figure 2-2b).** In LAC, MI results in higher production and net export revenue compared to REF due to LAC's comparative advantages in agricultural production. This highlights the increasing role that LAC may play in supplying global agricultural demands in a more interconnected world.

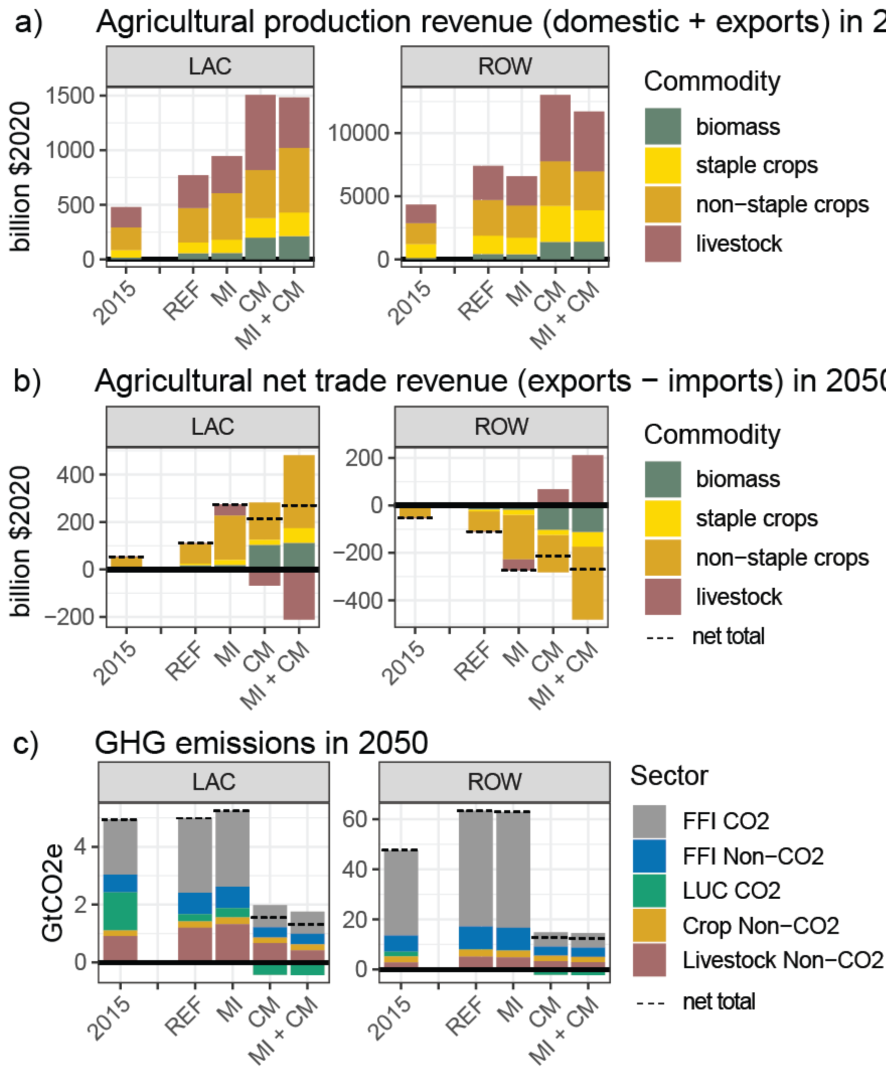

Figure 2-2. a) Agricultural production revenue (domestic + exports) by commodity, b) Agricultural net trade revenue (exports – imports) by commodity, and c) GHG emissions by sector in Latin America and the Caribbean (LAC) and rest-of-world (ROW) aggregated regions. 2015 = 2015 historical data. All other bars represent 2050 projections. REF = Reference, MI = Faster market integration on crops and livestock, CM = climate mitigation policy on CO_2 and non-CO_2 GHGs. Sensitivity scenarios shown in **Figure A-5**. Staple crops include the following GCAM commodity categories: corn, other grains, rice, roots and tubers, and wheat. Non-staple crops include the following GCAM commodity categories: oil crop, fiber crop, palm fruit, sugar crop and miscellaneous crop. FFI = emissions from fossil-fuel burning and industries, LUC = emissions from land use change.

LAC's role as an agricultural supplier is also evident in the outsized share of its GHG emissions that come from the agricultural, forestry, and other land-use (AFOLU) sectors. In the absence of climate policy, AFOLU GHG emissions (including LUC CO_2, and crop and livestock non-CO_2 emissions) make up a third of total GHG emissions in LAC in 2050 **(Figure 2-2c).** AFOLU emissions in LAC are 13% larger under increased market integration than in REF in 2050, while the same category of emissions decreases by 6% across ROW. Thus, while market integration may benefit LAC with increased agricultural revenues, it could add emissions reduction challenges.

On the other hand, under climate mitigation (CM) scenarios, both LAC and ROW reduce their GHG emissions dramatically from 2015 levels, across sectors. In LAC, there is a significant reduction in agricultural non-CO2 emissions, and an increase in land carbon sinks (afforestation) alongside reduced crop and/or livestock production in some areas. LAC's dual roles in supplying global agricultural needs as well as helping the world meet emissions reduction goals in the coming decades could thus pose trade-offs with one another, implying the need for more coordination between these two policy priorities. Because agricultural production and trade coming from LAC have important agro-economic and climate implications for the world, it is important to understand how the potential benefits and costs of increased agricultural activity will be distributed across the region. In the following two sections, we turn to understanding why market integration and climate mitigation drive certain outcomes across LAC's sub-regions.

2.3.2 The diversity in agro-economic futures across LAC

Across LAC, economies largely follow their historical preferences in producing, and net exporting and importing the same commodity types in 2050 REF as they did in 2015, though magnitudes increase **(Figure 2-3)**. However, uncertainty in the extent to which agricultural markets become integrated, as well as whether stringent land-oriented climate mitigation policy is pursued, has implications for the level of agricultural production and trade revenue in each LAC economy. In this next section, we analyze the implications of each global-scale driver, MI and CM, individually and in combination across LAC economies.

2.3.2.1 Effects of increased market integration

Overall, global market integration increases the level of imports and exports across regions. For LAC regions, increased market integration may bring increased opportunities through higher agricultural production revenues across the LAC economies (except for in N. South America—a region that includes Venezuela, French Guiana, Guyana, and Suriname), as each of these regions has comparative advantages in producing at least one type of commodity.

Under REF and MI, many South American regions (Argentina, Brazil, Uruguay, S. South America) are net exporters across commodity types in 2050. These regions stand to benefit most from greater market integration with higher agricultural production and export revenues across commodity types (**Figure 2-3)**. Oil crop (including soybeans and other nuts and seeds) production and exports bring significant revenue for all four of these economies, in contrast to all other LAC regions which import oil crops **(Figure A-7)**. Other dominant crops in these regions include miscellaneous high-value crops (including legumes, fruits, and vegetables), particularly in Brazil and S. South America, corn in Argentina and Brazil, and sugarcane in Brazil. Major livestock commodities for these regions include beef and dairy, particularly in Argentina and Uruguay, as well as poultry in Brazil and pork in S. South America.

Most of the remaining LAC regions—C. America & Caribbean, Colombia, and Mexico—are more mixed in terms of net imports and exports under MI; they have net exports of non-staple crops while having net imports of livestock and staple crops. In these regions, nearly all of the increase in production and export revenue under MI comes from increased production of high-value miscellaneous crops. Most of these regions have less livestock production and more imports under MI compared to REF, however, Mexico maintains similar levels under both scenarios. N. South America is the one region in LAC that decreases agricultural production revenue under MI relative to REF, largely in crop staples and livestock. It sees significant net imports of livestock under MI relative to REF. This is in line with its historical preferences as a net importer of all commodity types.

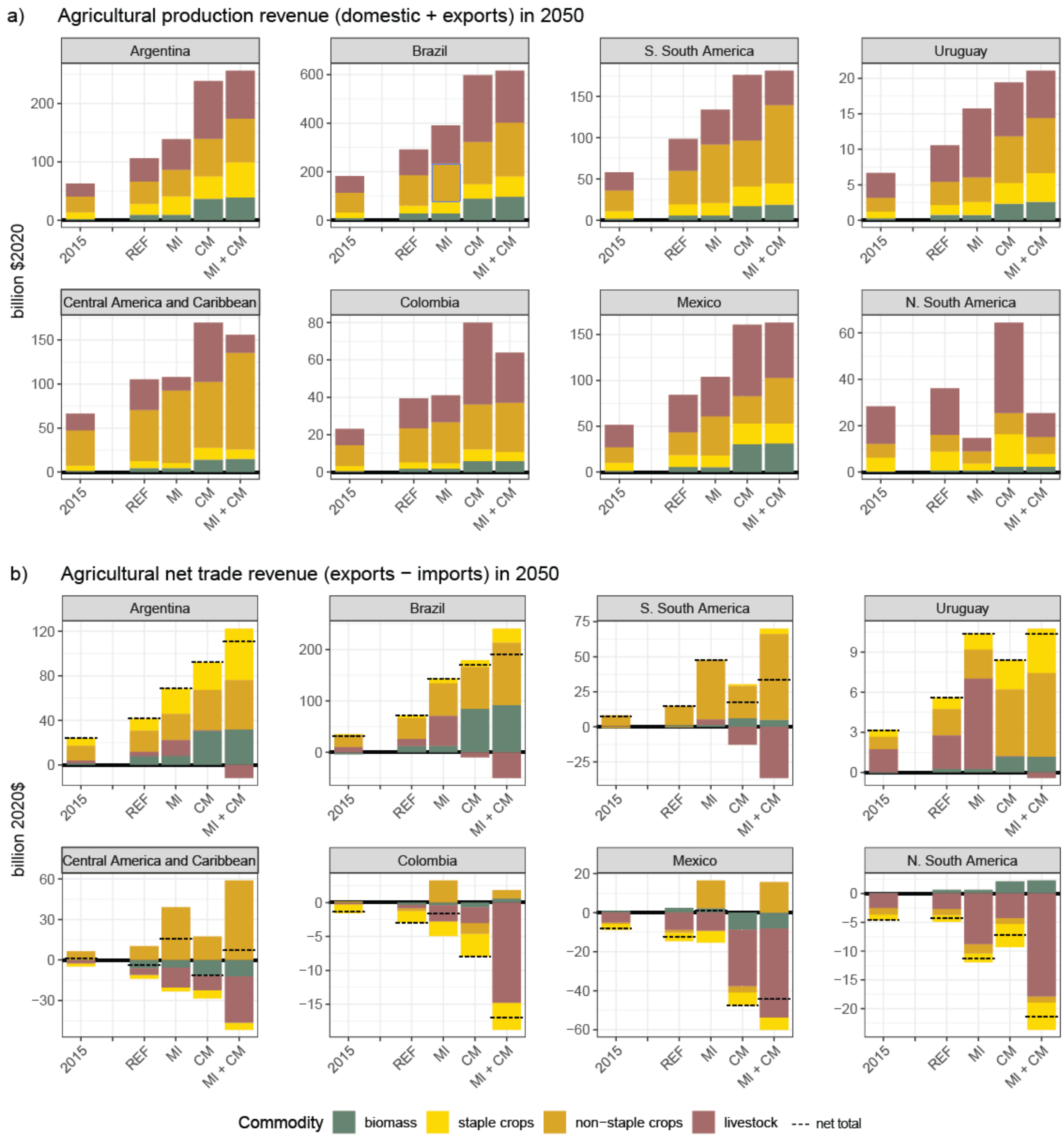

Figure 2-3. a) Agricultural production revenue (domestic + exports) and b) agricultural net trade revenue (exports – imports) by commodity across the 8 LAC economic regions. 2015 = 2015 historical data. All other bars represent 2050 projections. REF = Reference scenario, MI = Faster market integration on crops and livestock. CM = climate mitigation policy on CO_2 and non-CO_2 GHGs. Sensitivity scenarios shown in **Figure A-6**.

2.3.2.2 Effects of climate mitigation measures

Climate mitigation policy increases agricultural prices and consequently production revenues, export values, and import values across LAC and worldwide **(Figure 2-2a and b).** These impacts have been well documented in the literature. There are multiple mechanisms for how land-oriented climate mitigation policies increase agricultural prices, through land competition induced by afforestation and increased biomass production to fuel negative-emission bioenergy with carbon capture and sequestration (BECCS) technologies, as well as from reducing non-CO_2 emissions (Fujimori et al., 2022).

We observe the effects of each of these mechanisms in our CM scenarios in LAC. We isolate the impacts of the CO_2-targeted policies alone in the "CO2" scenarios in the SI. Crop prices increase in all regions due to increased land competition, leading to increased agricultural production and trade revenues across regions **(Figure A-6).** Furthermore, increases in biomass production and price lead to increased production revenues across regions, and increased net trade revenues in biomass exporting regions (especially Argentina and Brazil) by 2050.

Agricultural production value across commodities (particularly livestock) further increases as a result of pricing non-CO_2 GHG emissions, due to the additional costs of abating these emissions **(Figure 2-3a)**. There is a small decline in non-staple and meat consumption globally relative to REF **(Figure A-8).** In addition, pricing of non-CO_2 emissions has the effect of shifting livestock production and exports away from many LAC regions **(Figure 2-3b)**. Despite the overall increase in export revenue for LAC exporting regions, their net livestock exports decrease (and in Brazil and S. South America, reverse to net livestock imports) under CM compared to REF. Under CM, livestock production shifts and livestock exports increase in only a few regions globally (western Europe, East Asia, USA) which have lower livestock GHG emissions factors **(Figure A-9)**.

This effect persists under MI + CM, as regions that exported livestock (Argentina, Brazil, S. South America, and Uruguay) under MI now have small net livestock imports **(Figure 2-3b)**. In Mexico and Colombia, climate mitigation policy also has the effect of reducing miscellaneous crop exports. Climate policy thus introduces another factor, emissions mitigation potential, alongside traditional factors (natural resources and agricultural productivity) in determining an economy's comparative advantage in agricultural production, which becomes important in shifting patterns of production and trade, especially for livestock.

We compare our core CM scenarios against sensitivity scenarios with differentiated livestock MAC curves by region (see "CM (diff. MAC)" sensitivity cases in **Figure A-6**), in which LAC regions have less livestock GHG emission mitigation potential than under the core CM scenarios. The ability to mitigate more livestock GHG emissions as a result of steeper livestock MAC curves in the core CM cases allows LAC regions to maintain higher levels of livestock production and net exports (or less net imports). Improved livestock emissions mitigation in LAC could come from a variety of strategies, e.g., animal breeding, dietary manipulation, or rumen manipulation to reduce enteric methane from livestock (Congio et al., 2021). Thus, improving livestock emission mitigation management options creates flexibility to reduce non-CO_2 emissions without compromising production and revenue (Frank et al., 2019).

In summary, climate mitigation policy introduces two main effects: increasing overall agricultural production prices and decreasing livestock production in many LAC regions due to their lack of comparative advantages in livestock emissions mitigation. However, many of LAC's regions maintain their comparative advantages in producing some crop types for export. Because CM introduces opposing effects on crop versus livestock agricultural production revenues in several LAC regions, its combination with market integration could create potentially non-linear effects. In the next section, we analyze these complex interactions.

2.3.2.3 Complex interactions between market integration and climate mitigation

Increased market integration and climate mitigation policy may hold opportunities for many of LAC's economies by increasing overall agricultural production and trade revenues. However, outcomes are heterogeneous across regions and commodity types. Increased opportunities in one sector of agricultural production can sometimes be outweighed by decreases in others. Outcomes derived from combining MI and CM are complex, and in some cases non-linear.

Across LAC economies, both the MI and CM effects increase import values **(Figure 2-4a)**. As a result, MI + CM leads to the highest import values across LAC regions. In all regions, the increase in livestock imports under MI + CM is larger than the sum of livestock imports under MI and CM individually **(Figure A-10).** This highlights the non-additive effects that result from these two drivers in combination. In the combined scenario, both MI and CM effects also increase export values **(Figure 2-4b)** as a result of increases in crop export share (through MI) and increases in the price of agricultural exports (through CM). Though all regions decrease their livestock export share due to CM, this is outweighed by the overall increase in agricultural prices.

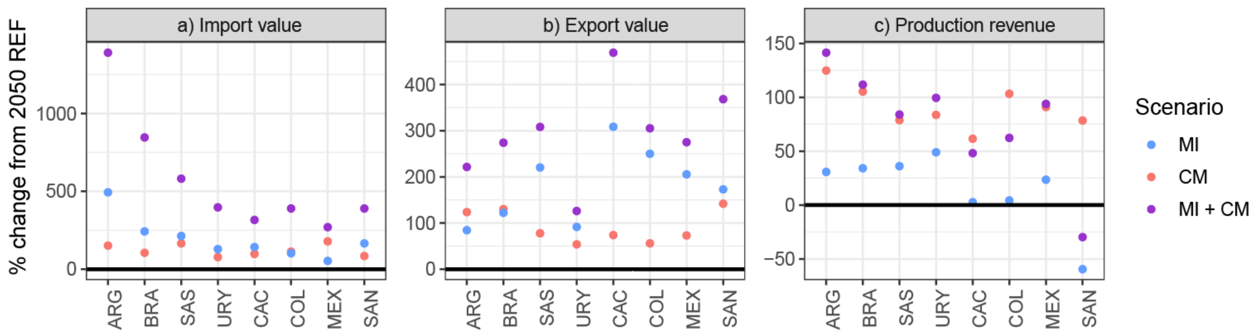

Figure 2-4. Percentage change compared to 2050 REF in a) gross agricultural import value b) gross agricultural export value and c) agricultural production revenue (domestic + exports) across the 8 LAC regions for each scenario in 2050. REF = Reference scenario, MI = Faster market integration on crops and livestock. CM = climate mitigation policy on CO_2 and non-CO_2 GHGs. Regions: ARG = Argentina, BRA = Brazil, SAS = S. South America, URY = Uruguay, CAC = Central America & Caribbean, COL = Colombia, MEX = Mexico, SAN = N. South America.

In LAC's net exporting regions (Argentina, Brazil, S. South America, and Uruguay), MI + CM leads to the highest production revenue across scenarios **(Figure 2-3a; Figure 2-4c)**. This is due to the CM effect of increasing the prices of agricultural commodities as well as the MI effect of expanding market share for these regions, due to their comparative advantages. Decreases in livestock production revenue under MI + CM relative to CM are outweighed by increases in crop production revenue as these regions maintain their crop market share. Mexico, despite not being a net exporter of all commodity types, sees a similar pattern, in that increases in non-staple (miscellaneous) crop production outweigh decreases in livestock and staple crop production.

Under MI + CM, N. South America continues to lose producer revenue relative to REF, although by less than under MI alone **(Figure 2-4c)**. C. America & Caribbean and Colombia show examples of non-linearity occurring when MI and CM are combined. Though MI marginally increases production revenue relative to REF, when combined with CM, it decreases production revenue relative to CM (which has the highest production revenue across scenarios). Under MI, decreases in livestock production revenue relative to REF are outweighed by increases in crop production revenue. However, the opposite occurs under MI + CM relative to CM, highlighting the non-linear outcomes that may result from combining these two drivers.

2.3.3 Social and environmental trade-offs across LAC's water-economy regions

Increased economic opportunities resulting from global market integration or climate mitigation could potentially result in disparate benefits and challenges faced by consumers or environmental sectors. In the next section, we identify social and environmental impacts that should be considered in order to mitigate the unintended negative consequences of increased market integration and climate mitigation policies.

2.3.3.1 Disparate outcomes for producers vs. consumers

Agricultural production revenue is projected to increase across most water-economy regions (WERs) in LAC by 2050, and more so with trade integration and climate mitigation measures **(Figure 2-5a)**. However, consumer agricultural expenditures are also projected to increase **(Figure 2-5b)**, presenting a potential risk for food insecurity (due to affordability concerns) for low-income groups in these regions.

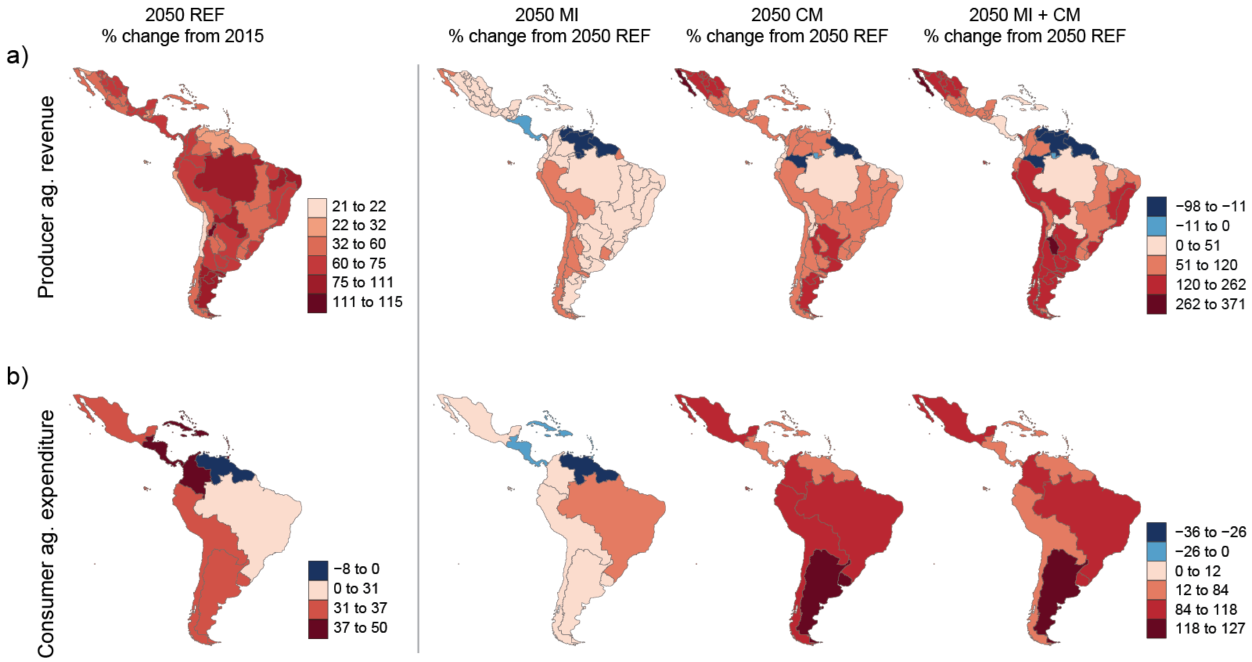

Figure 2-5. a) producer agricultural revenue by water-economy region (WER) and b) consumer agricultural expenditure per capita by economic region. Maps on the left show the % change between 2015 and 2050 REF. Maps on the right show % change from 2050 REF in the MI, CM, and MI + CM scenarios in 2050. An important caveat is that we are only able to derive consumer agricultural expenditure per capita at the economic region level resolution, therefore this metric is an average across WERs in the same economic region and does not reflect differential spending.

Under MI and CM, only a few WERs have lower producer revenue relative to REF in 2050, including WERs in C. America, N. South America, Colombia, and Brazil. Most of these WERs also have lower producer revenue with MI + CM combined **(Figure 2-5a)**. Meanwhile, the majority of LAC WERs have higher producer revenue as a result of the MI and CM drivers, in many cases seeing the highest percentage increases relative to REF with both drivers combined. However, despite having increases in producer revenue under MI relative to REF, several WERs in C. America & Caribbean and Colombia have decreases in producer revenue under MI + CM relative to CM, i.e., the non-linear effect described in Section 2.3.2.3 (**Figure 2-7)**. Overall, while increased revenues across much of the region may benefit agricultural producers, they may pose challenges for consumers.

As markets open up globally, consumers in comparatively advantaged producing regions (like many WERs in LAC) may be exposed to higher global prices, as a result of local production being increasingly used for exports, requiring consumers to increase their consumption of imported commodities (**Figure A-11)**. Thus, under MI, most regions in LAC see higher consumer agricultural expenditure relative to REF, except in C. America & Caribbean and N. South America **(Figure 2-5b)**. Under MI, the highest increases (by percent) in consumer expenditure relative to REF across LAC are in Brazil. It will be important for policymakers to address the challenges that increased consumer expenditure could pose, particularly for low-income groups within the region. For example, based on SSP2 projections, the N.E. South America S. Atlantic Coast and Amazon WERs in Brazil (WERs #32 and #33 in **Figure 2-1**) could rank among the WERs with the lowest per capita GDP in LAC in 2050 (see **Figure A-12**, Murakami & Yamagata, 2019), representing WERs that could experience particularly adverse outcomes as a result of increased consumer expenditure.

CM induces higher consumer prices across the region (and worldwide), consistent with literature highlighting food affordability concerns associated with climate mitigation measures (Cui et al., 2022; Fujimori et al., 2022; Giuliani et al., 2022). These percentage increases are much larger than those experienced under MI only, with the largest increases in Argentina **(Figure 2-5b)**.

With MI + CM combined, Mexico, Brazil, and Argentina have similarly high percentage increases in consumer agricultural expenditure relative to REF as they do under CM only **(Figure 2-5b)**. Meanwhile, other LAC regions have lower consumer expenditure under MI + CM relative to CM. For these regions, market integration thus serves as a potential way to mitigate increases in consumer expenditure that result from climate mitigation policy. For Mexico, Brazil, and Argentina, however, other mechanisms (e.g., consumer subsidies) may need to be considered to counteract the adverse impacts of increased market integration on their populations. Indeed, ensuring food security is a top priority for policymakers, evidenced by countries limiting global market integration of their key export crops to protect domestic consumers (Clapp, 2017). However, limiting global market integration could impact economic opportunities across LAC, as discussed above, and affect consumers around the world (Taherzadeh et al., 2021).

2.3.3.2 Impacts across integrated land-water-climate systems

Land use changes are the result of competition between several different land types, including crop, pasture, and forest land. In the absence of additional drivers (REF), crop and pastureland are projected to increase across much of LAC by 2050 **(Figures 2-6a and 2-6b)**, while forest land decreases **(Figure A-13)**. Water withdrawals are also projected to increase **(Figure 2-6c)**.

The market integration and climate mitigation drivers result in diverse and often opposing changes in land, water, and emissions across LAC relative to REF. Under MI, much of LAC has more cropland than in REF **(Figure 2-6a)**, with the exceptions of WERs in N. South America (because of their decreases in agricultural production), and WERs in Uruguay (which instead expand pastureland to support increased beef and dairy production). Pastureland changes are more mixed overall under MI, depending on the comparative advantages of a given WER **(Figure 2-6b)**. Meanwhile, further deforestation occurs relative to REF across much of LAC **(Figure A-13)**, a trade-off that results from increased agricultural production.

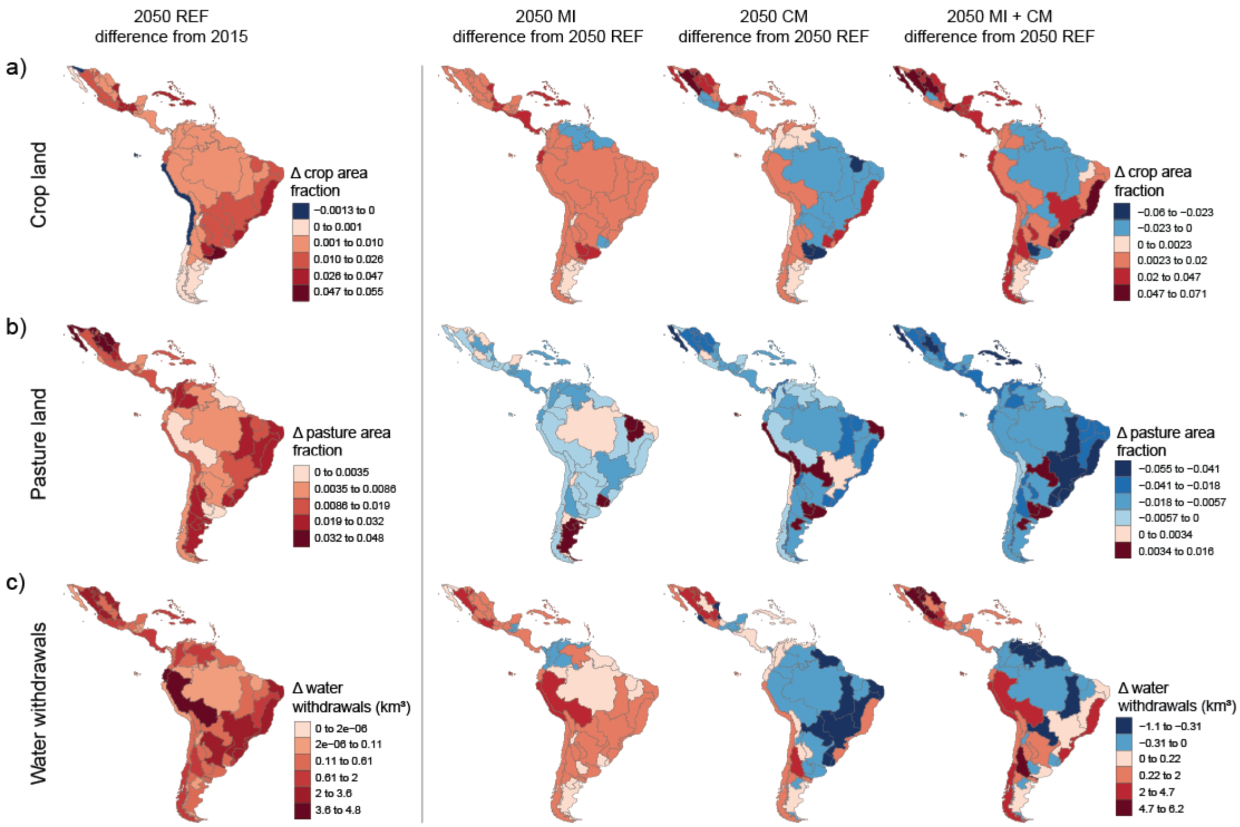

Figure 2-6. a) cropland (including purpose-grown biomass crops), b) pastureland, and c) agricultural (irrigation and livestock) water withdrawals by WER. Maps on the left show difference from 2015 under REF in 2050. Maps on the right show percent change from REF under the MI, CM, and MI + CM scenarios in 2050.

On the other hand, CM results in less land use for crops across much of LAC relative to REF, particularly in inland Brazil, correlating with increases in forest land to increase land carbon sinks **(Figure 2-6a; Figure A-13)**. This highlights the trade-off in pursuing agricultural production and afforestation as a climate mitigation policy in some WERs. However, CM still results in more cropland in several WERs relative to REF, with some of the highest increases in Mexico and the Uruguay-Brazil S. Atlantic Coast of Brazil and Uruguay (WERs #39 and #49 in **Figure 1**). CM results in many more WERs having less pastureland than REF **(Figure 2-6b)**, due to the reduction in livestock production share, as discussed in Section 2.3.2.2. However, some WERs without much forest land have increases in pastureland (often unmanaged pasture), which serves as a carbon sink if converted from cropland.

Because many WERs experience opposing changes driven by MI and CM individually, cropland changes from combining MI + CM are often in between the two opposing changes and may be either higher or lower than in REF **(Figure 2-6a)**. Meanwhile, for several WERs in Mexico, Central America, and the Caribbean, and along the Atlantic and Pacific coasts of South America which have higher cropland under both MI and CM than REF, MI + CM leads to the highest increases in cropland experienced across scenarios. Pastureland decreases in all but a few WERs in S. South America and Argentina **(Figure 2-6b)**.

Under MI, water withdrawals are higher across much of LAC than in REF **(Figure 2-6c)**. Changes in water withdrawals across scenarios highlight the importance of water availability in determining comparative advantages, and, thus, affecting the production of irrigated versus rainfed crops. For example, Orinoco and NE S. America S. Atlantic coast WERs in N. South America (#29 and #30) have more irrigated cropland relative to REF, despite having less cropland overall. Meanwhile WERs in C. America & Caribbean and Colombia have more cropland for rainfed crops but less irrigated cropland and water withdrawals. Under CM, much of LAC has less water withdrawals, while several WERs in Mexico, coastal South America and much of Argentina have more water withdrawals. Though there are less water withdrawals for livestock across all of LAC **(Figure A-14),** WERs that have higher overall water withdrawals do so because of increases in irrigation. The Colorado WER in Argentina (#58), and Rio Lerma (#8) and Rio Grande (#16) WERs in Mexico, have the highest water withdrawals under MI + CM, resulting from high water withdrawals under both MI and CM. These WERs are contained within LAC basins which have among the highest water withdrawals to basin runoff ratios, approaching moderate water scarcity under MI + CM in 2050 **(Figure A-3).** Such WERs exemplify cases in which water demands (due to increased agricultural production) may drive water scarcity concerns**.** Water storage, distribution, and irrigation infrastructure can be costly; thus, targeted investments could help WERs, which may have increased water withdrawals capitalize on opportunities and reduce water scarcity pressures (Rozenberg & Fay, 2019).

2.3.3.3 Identifying hotspot WERs across scenarios and dimensions

Figure 2-7 shows percentage differences relative to the REF scenario for several economic and environmental metrics discussed above, across all WERs in LAC, as a result of the MI and CM drivers, individually and combined. WERs that have percentage differences in the highest or lowest 10^{th} percentile across all WERs for each metric and scenario (i.e., the most extreme) are shown in bold, and we can thus identify WERs that emerge as hotspots, experiencing extreme changes across multiple economic and environmental dimensions as a result of the integrated, multi-sectoral nature of the agro-economic system. We can also identify whether these outcomes are driven by increased global market integration, climate mitigation measures, or both.

		MI					CM					MI + CM				
		Prod. revenue	Cons. expend.	Crop land	Pasture land	Water wd.	Prod. revenue	Cons. expend.	Crop land	Pasture land	Water wd.	Prod. revenue	Cons. expend.	Crop land	Pasture land	Water wd.
MEX	1. Baja California	68	7	**46**	2	30	**264**	116	**210**	-7	**118**	**371**	115	**266**	-9	**159**
	2. Mexico NW Coast	25	7	20	1	25	132	116	60	-9	25	129	115	76	-12	44
	3. North Gulf	38	7	10	-2	18	59	116	6	-2	-5	87	115	16	-6	12
	4. Yucatan Peninsula	43	7	17	**15**	**66**	99	116	**96**	-5	-8	119	115	104	-8	40
	5. Mexico Interior	21	7	25	3	23	**162**	116	**94**	-5	8	160	115	137	-7	35
	6. Pacific Central Coast	19	7	14	4	**49**	49	116	-4	-1	-11	48	115	8	-5	31
	7. Papaloapan	32	7	12	-6	34	60	116	9	-4	1	76	115	19	-9	28
	8. Rio Lerma	15	7	7	8	17	67	116	-13	0	**48**	54	115	-6	-3	66
	9. Rio Verde	30	7	13	2	14	88	116	6	-4	40	91	115	18	-8	51
	10. Grijalva Usumacinta	34	7	9	1	**47**	62	116	7	-4	-8	89	115	14	-8	34
	11. Rio Balsas	18	7	8	5	40	68	116	0	-1	7	56	115	9	-5	45
	12. Southern Central America	37	7	14	-21	36	28	116	10	-4	-30	63	115	20	-11	4
	13. Isthmus of Tehuantepec	35	7	14	-6	**44**	83	116	24	-7	-12	94	115	32	-11	21
	14. California	20	7	24	7	4	**180**	116	32	-1	**59**	**266**	115	79	-3	77
	15. Lower Colorado	55	7	31	7	19	129	116	66	-1	**73**	227	115	117	-2	**118**
	16. Rio Grande	25	7	18	8	8	**153**	116	**106**	-4	41	164	115	**144**	-6	60
CAC	17. Caribbean	**2**	-15	12	**-26**	10	52	**66**	2	-6	1	30	36	15	-16	8
	18. Yucatan Peninsula	19	-15	11	-23	-3	45	**66**	2	-2	8	73	36	18	-17	6
	19. Grijalva Usumacinta	24	-15	13	-23	**-12**	48	**66**	8	-3	-1	87	36	28	**-17**	-16
	20. Southern Central America	**-1**	-15	15	-22	18	64	**66**	7	-3	5	44	36	30	-16	29
	21. Caribbean Coast	16	-15	17	-23	**-8**	67	**66**	23	-4	8	93	36	43	**-17**	7
	22. Colombia Ecuador Pacific Coast	**70**	-15	30	-16	**-27**	62	**66**	31	1	-7	183	36	77	-13	**-44**
COL	23. Caribbean Coast	4	1	9	-5	-3	100	108	9	-4	10	54	91	13	-6	-5
	24. Orinoco	7	1	12	-3	-3	90	108	7	-3	-3	58	91	17	-5	-22
	25. Colombia Ecuador Pacific Coast	11	1	9	-5	-1	43	108	2	-1	8	33	91	2	-6	-4
	26. Magdalena	3	1	9	-5	**-3**	108	108	0	-1	4	60	91	10	-3	-2
	27. Amazon	19	1	7	-2	1	**-30**	108	**-44**	**-17**	**-61**	**-35**	91	**-47**	-17	**-65**
SAN	28. Caribbean Coast	**-62**	**-36**	**-33**	**-36**	**-14**	89	77	23	-2	3	**-33**	**16**	-4	-7	-18
	29. Orinoco	**-62**	**-36**	**-23**	**-40**	8	77	77	3	0	-9	**-32**	**16**	-24	-7	-13
	30. NE S. America S. Atlantic Coast	**-38**	**-36**	**-7**	**-48**	14	**-21**	77	**-63**	**-16**	**-69**	**-48**	**16**	**-66**	-17	**-68**
	31. Amazon	**-12**	**-36**	**-6**	**-46**	**-21**	**-1**	77	**-47**	-13	-31	**-10**	**16**	**-50**	-14	-38
BRA	32. NE S. America S. Atlantic Coast	62	**13**	**42**	**24**	22	**-98**	96	**-98**	**-32**	-25	**-97**	94	**-98**	**-32**	**-54**
	33. Amazon	31	**13**	20	**17**	28	**7**	96	-41	**-22**	**-46**	26	94	-33	**-25**	-37
	34. N.Brazil S. Atlantic Coast	44	**13**	24	11	22	16	96	**-42**	**-20**	**-38**	23	94	**-35**	**-22**	**-54**
	35. Tocantins	27	**13**	13	3	17	118	96	-20	-7	-26	89	94	-4	-11	-37
	36. E. Brazil S. Atlantic Coast	32	**13**	19	5	10	40	96	-4	**1**	-19	86	94	25	-8	1
	37. Parnaiba	37	**13**	19	13	17	62	96	-12	-8	**-31**	100	94	7	-14	-22
	38. Sao Francisco	40	**13**	18	4	17	80	96	-3	-4	-13	123	94	25	-10	7
	39. Uruguay Brazil S. Atlantic Coast	45	**13**	15	2	13	118	96	34	-7	12	143	94	54	-14	26
	40. La Plata	37	**13**	5	-6	7	109	96	-2	0	-3	105	94	11	-9	1
SAS	41. Colombia Ecuador Pacific Coast	49	3	18	**-25**	4	42	89	3	-2	1	77	76	19	-7	3
	42. Amazon	64	3	26	4	33	59	89	12	-3	-2	126	76	32	-5	25
	43. S. Chile Pacific Coast	67	3	35	-2	29	70	89	30	-1	28	149	76	76	-5	65
	44. Peru Pacific Coast	**74**	3	**41**	-4	30	69	89	23	**2**	22	153	76	72	-3	61
	45. La Puna	**81**	3	34	3	22	40	89	15	1	7	110	76	44	**0**	27
	46. La Plata	13	3	8	4	18	83	89	-19	**5**	-23	37	76	-7	**4**	-22
	47. N. Chile Pacific Coast	**91**	3	**57**	4	42	54	89	26	1	29	**230**	76	138	**-2**	**118**
	48. S. Argentina S. Atlantic Coast	11	3	20	14	25	127	89	28	-3	-27	83	76	41	-3	**-67**
URY	49. Uruguay Brazil S. Atlantic Coast	39	8	**-1**	**21**	10	79	122	11	-3	-29	108	116	28	-5	-11
	50. La Plata	54	8	**-6**	**21**	15	75	122	20	-4	-25	87	116	33	-7	-11
ARG	51. S. Chile Pacific Coast	68	9	35	14	5	**10**	**127**	-26	-6	**-35**	42	**125**	-6	-6	-31
	52. La Puna	48	9	**46**	**19**	9	39	**127**	**-85**	**-17**	-16	19	**125**	**-83**	**-17**	-31
	53. Mar Chiquita	30	9	7	-1	16	103	**127**	3	-3	11	149	**125**	11	-6	28
	54. Salinas Grandes	57	9	24	8	40	130	**127**	44	-2	31	**263**	**125**	91	-3	**99**
	55. La Plata	30	9	7	-2	23	123	**127**	0	-4	-1	128	**125**	7	-6	16
	56. Pampas	27	9	7	2	16	104	**127**	-14	**4**	-13	127	**125**	-6	**2**	-7
	57. N. Argentina S. Atlantic Coast	29	9	6	-2	23	125	**127**	-11	**4**	-7	127	**125**	-2	**2**	12
	58. Colorado	**70**	9	**43**	3	**55**	117	**127**	77	-2	**76**	**242**	**125**	**152**	-4	**172**
	59. Negro	**68**	9	24	9	**50**	105	**127**	**93**	-1	45	**231**	**125**	**145**	-2	**131**
	60. Central Patagonia Highlands	36	9	39	13	10	**169**	**127**	**91**	**1**	-9	143	**125**	**169**	**1**	-18
	61. S. Argentina S. Atlantic Coast	34	9	23	14	4	**157**	**127**	89	-2	**51**	127	**125**	**141**	-2	62

Figure 2-7.

Percentage difference relative to REF in 2050 across all LAC water-economy regions (WERs) under the MI, CM, and MI + CM scenarios across several economic and environmental metrics: producer agricultural revenue, consumer agricultural expenditure per capita, cropland (including purpose-grown biomass), pasture land, and agricultural water withdrawals. Positive percent difference is shaded in red, negative percent difference is shaded in blue, with darker shading indicating higher magnitude. Bold values indicate the 10th and 90th percentile of basins for a given metric.

For example, several WERs in N. South America and Brazil experience extreme decreases across economic and environmental dimensions under MI + CM relative to REF. For some, like the Caribbean Coast and Orinoco WERs in N. South America (#28 and #29 in **Figure 2-1**), changes are driven by MI decreasing market share. On the other hand, changes in the NE S. America S. Atlantic Coast and Amazon WERs in Brazil (#32 and #33) as well as the Amazon in Colombia (#27) are driven by CM, because these WERs afforest while reducing agricultural production. Finally, some WERs, like the NE S. America S. Atlantic Coast and Amazon WERs in N. South America (#30 and #31), are driven by both factors, experiencing extreme decreases in all scenarios relative to REF.

Meanwhile, several WERs in Argentina and Mexico experience extreme increases across multiple economic and environmental dimensions under MI + CM relative to REF. Increases relative to REF in economic dimensions are generally much higher under CM than under MI, due to the increasing agricultural prices. Baja California WER in Mexico (#1) has significantly higher producer revenue, cropland, and water withdrawals under MI + CM, driven by the CM dimension. Meanwhile, the Colorado WER in Argentina (#58) has higher producer revenue, cropland, and water withdrawals, which are driven by both MI and CM dimensions. This highlights the complex ways in which different global-scale drivers can result in different WERs seeing severe changes (Birnbaum et al., 2022). Identifying such hotspot WERs and the driving forces of the extreme outcomes within them, can be valuable to decision-makers trying to identify areas in which to prioritize multi-sectoral planning or targeted investments.

2.4 Discussion and Conclusions

Increased agricultural production and exports from LAC could represent a significant opportunity for several of LAC's economies in the coming decades. Total net export revenue across LAC could reach \$110-\$270 billion annually by 2050, with regions like Argentina, Brazil, S. South America, and Uruguay significantly growing their share of net agricultural exports to the world. Such exports will be critical to meeting agricultural demands around the world.

However, unsustainable or inequitable outcomes in particular regions or on particular groups within society could result in significant trade-offs with these economic opportunities, potentially preventing these opportunities from fully materializing. For example, increased producer revenue under either increased market integration or climate mitigation measures could also cause increased consumer agricultural expenditures, which poses a potential risk of food insecurity for low-income groups. Under climate mitigation measures, increases in consumer expenditure could be particularly severe across all regions. Market integration might serve as a potential way to mitigate increases in consumer expenditure that result from climate mitigation in some regions (C. America & Caribbean, Colombia, N. South America, S. South America, and Uruguay, as identified in our study), but additional policy mechanisms (e.g., to redistribute some of the gains of market integration from producers to consumers) may be needed in others (such as Mexico, Brazil, and Argentina). Policies limiting market integration to protect domestic consumers could limit economic opportunities and further affect consumers around the world (Clapp, 2017).

Agricultural production and emission reduction goals could also have trade-offs with one another (Bataille et al., 2020; Morris et al. 2020). While increased market integration can benefit many LAC regions with increased agricultural revenues, it could increase deforestation and add emissions reduction challenges. On the other hand, pursuing land-based climate mitigation strategies, such as afforestation, could limit agricultural production in some areas.

Meanwhile, currently dominant pastoral livestock management in many LAC regions has higher GHG emissions and is worse for global sustainability than more intensified, feed-based management (Congio et al., 2021; Havlík et al., 2014; Herrero et al., 2016). Pastoral livestock management may pose risks of lost production revenue in a world pursuing stringent climate mitigation, as shown in our results. However, switching away from pastoral management towards concentrated feed-based management could pose trade-offs for local sustainability, by increasing local water pollution (Burkholder et al., 2007) or causing sanitary and animal well-being concerns (Havlík et al., 2014). This highlights complex trade-offs that may occur across scales.

Both market integration and climate mitigation drivers are important in affecting economic and environmental outcomes in LAC, though depending on the stringency of climate mitigation needed, impacts on land competition and consequently agricultural prices could be particularly severe. Here we demonstrate the importance of considering the interactions between drivers, noting the complex and non-linear outcomes that may result. For example, in Central America and Colombia, increased market integration alone may increase agricultural production revenue, yet when combined with climate mitigation policy, it leads to decreased agricultural production revenue. Given such interactions, more integrated planning between agro-economic development and climate mitigation objectives should be considered to achieve balanced outcomes and help navigate trade-offs, as described above.

Our results show considerable heterogeneity in impacts across regions, environmental sectors, and groups within society. For example, all water-economy regions in Argentina have increased producer revenue as a result of market integration and climate mitigation, contributing to Argentina's overall status as a major net exporter. However, only a few WERs (e.g., Colorado, #58) have particularly large increases in water withdrawals, highlighting where targeted investments in water infrastructure could help capitalize on opportunities and reduce water scarcity pressures. Most WERs are already pursuing multiple objectives, including water supply, land development and management, and climate mitigation measures (Alcoforado de Moraes et al., 2021; COIRCO, 2014). Our study provides additional context to understand how their goals might be affected by global-scale drivers, so that they can better align their priorities if desired.

2.5 Limitations and Future work

There are several caveats to consider when interpreting the results of our study. We model market integration and climate mitigation drivers in a stylistic manner to derive broad insights across all of LAC, rather than modeling specific climate policies or trade agreements that may be undertaken by individual countries. Similarly, the metrics we consider are highly stylized; for example, producers and consumers are not two distinct groups but consist of many people who may be part of both groups. Therefore, the line between opportunities and challenges experienced by each of these groups is blurred. While we consider outcomes spanning scales, there could be additional trade-offs that our analysis does not consider, such as impacts on water quality or biodiversity (Flachsbarth et al., 2015), or increased emissions resulting from the transportation of traded commodities (Zimmermann et al., 2018). Indeed, increased agricultural market integration, leading to increased export emissions from LAC, would further increase climate mitigation pressures. Many important trade-offs could occur at even finer scales (Khan et al., 2021), such as at a gridded spatial or monthly temporal resolution and are not captured by our analysis. The key takeaways from our study are not the exact magnitudes or percentage changes that a given region or basin may experience along any given economic or environmental dimension, but rather the broad trends resulting from market integration and climate mitigation drivers independently and in interaction with each other.

The two drivers considered in this study highlight how natural endowments of land and water, as well as technological factors, such as livestock management practices and emissions mitigation potential, are important factors in affecting comparative advantages and how and where agricultural production and trade may evolve over the coming decades. Indeed, several technological factors, including those not discussed here, such as improved crop or livestock yields (Flachsbarth et al., 2015; Schneider et al., 2022), as well as demand-side changes, such as dietary preference shifts (Eker et al., 2019), could have a significant impact on agricultural production and trade patterns. Future work can consider including market integration and climate mitigation alongside multiple such drivers in large-ensemble scenario discovery studies (e.g., Lamontagne et al., 2018) to explore multiple uncertain dimensions of global change and their interactions.

Our study has focused on broadly identifying interactions between market integration and climate mitigation across the LAC region. Specific regions or basins identified here as experiencing extreme changes as a result of market integration or climate mitigation measures could also benefit from additional detailed study.

3. Essay 2: The future evolution of natural gas trade

This essay is based on: Yarlagadda, B., G. Iyer, M. Binsted, P. Patel, M. Wise, and J. McLeod (2024). The future evolution of global natural gas trade. *iScience.* https://doi.org/10.1016/j.isci.2024.108902, *and includes additional parameter updates.*

3.1 Introduction

Natural gas is an important source of energy with widespread use in the electricity, industry, and buildings sectors (IGU, 2022). Natural gas combustion results in low emissions compared to the combustion of other fossil fuel sources of coal and refined petroleum products (Holz et al., 2015). Natural gas-fired power plants serve as a source of firm electricity capacity which can be particularly important as countries transition their grids to utilize higher levels of variable renewable electricity sources (Bistline & Young, 2022). Natural gas trade is a key contributor to GDP in several exporting economies, e.g., contributing to 12% of GDP in Qatar and 6% of GDP in Russia (World Bank, 2021), and it has been important for meeting energy demands in many importing countries, particularly in Asia and Europe (IGU, 2022). However, dependence on natural gas imports, particularly pipeline gas imports, also poses energy security risks for importing countries due to the fact that pipeline gas trade entails a fixed source and destination. For example, recent geopolitical events have highlighted energy security risks in Europe, which is heavily reliant on natural gas imports via pipeline (IEA, 2023a; IGU, 2023). The desire to reduce import dependency has resulted in increased gas prices and concerns about meeting energy demands in Europe (Cui et al., 2022; Lau et al., 2022; Pedersen et al., 2022).

Across energy commodities, there is a wide range in the physical distances across which trade occurs. Commodities like oil and coal, which can be readily shipped, are more easily traded globally, while commodities like electricity, which requires a network of transmission lines, have much more localized trade. Natural gas falls in the middle. Historically, most natural gas trade occurred through pipeline networks, which are physically limited to a regional scale (Paltsev, 2015). However, the trade of liquefied natural gas (LNG), which is first cooled to liquid form for transport and then re-gasified at its destination, has been growing rapidly. LNG exports have more than tripled since 2000 and made up just over half of international gas trade in 2018 (Molnar, 2022; IEA, 2019). Emerging LNG infrastructure, such as floating storage and regasification units offer further potential for LNG to be supplied to more regions globally, beyond those regions with onshore gas terminals in place. Natural gas trade capacity is set to increase further in the coming decades; gas trade infrastructure under construction and proposed corresponds to an increase of 85% and 28% in LNG terminal (liquefaction, storage, and regasification) and pipeline capacity, respectively (Yang et al., 2022). Natural gas trade is unique among energy commodities in that the two dominant means of trade have very different physical and market characteristics, and as a result, have different future growth expectations (see Table S1 for further details).

Several factors could affect the future evolution of natural gas trade. On the supply-side, increases in resource availability could shift regional production, trade, and consumption patterns around the word. For example, in the United States, the shale gas revolution enabled the US to switch from being a net importer of LNG to a major net LNG exporter (Egging-Bratseth et al., 2021). On the demand-side, reduced trade, and transportation service demands due to the COVID-19 pandemic temporarily lowered gas demands (EIA, 2022a). Regional transitions to a low-carbon economy and the availability of renewable energy and electricity storage technologies could also lower demand for natural gas. On the other hand, regions transitioning away from higher-emission fuels like coal could have higher demands for natural gas in the near-term (EIA, 2022b). Trade-related factors, such as the availability and cost of different trade infrastructure or geopolitical barriers to trade, could affect the trajectory of overall natural gas production, consumption, and trade, as well as the relative growth of LNG versus traded pipeline gas across different regions. It is therefore important to consider the interactions between multiple factors affecting natural gas trade, as well as the evolution of the natural gas trade sector within the context of other sectors of the energy system and the economy.

3.1.1 Literature review

Several studies have evaluated the future dynamics of fossil fuel markets. Studies have considered the dynamics of specific fuels with detailed sectoral models, e.g., Auger et al., 2021 for coal and Madhavi & Nuttall, 2023 for oil. Other studies have looked broadly across the energy system to understand how fossil fuels will compete with other technologies under a range of scenarios varying economic growth, deployment of transitions to low carbon energy systems, and fossil fuel availability (Bauer et al., 2015; Kriegler et al., 2016; McCollum et al., 2014; McGlade and Ekins, 2015).

Similarly, models analyzing the future evolution of natural gas trade can be generally grouped into two classes: 1) detailed natural gas sectoral models and 2) multi-sectoral models that include some representation of natural gas supply and demand (see Table S2 for previous studies of each class). Detailed natural gas sectoral models generally represent pipeline gas and LNG as distinct trade pathways, and many of them represent detailed supply chain agents within each trade pathway (e.g., Egging et al., 2010; Egging-Bratseth et al., 2021; Meza et al., 2021). However, these models generally do not consider the interactions and competition across natural gas and other energy supply technologies, nor do they consider the interactions across multi-sectoral demands for natural gas. On the other hand, multi-sectoral models aim to provide more holistic representation of the energy system with a full suite of supply technologies to meet endogenous, multi-sectoral demands (e.g., Jewell et al., 2014, 2016, 2018; McJeon et al., 2014; Paltsev, 2014; Pedersen et al., 2022). However, these models have historically not explicitly included representation of pipeline gas and LNG trade pathways and investments required for each.

Recently, a few multi-sectoral modeling studies have included explicit representation of pipeline gas and/or LNG trade pathways (Feijoo et al., 2018; IEA, 2022; Shepard et al., 2022). IEA's World Energy Outlook 2022 provides global-level pipeline gas and LNG trade projections for scenarios representing different levels of climate policy achievement (comparison plots with our results shown in **Figures B-9 to B-13**), and qualitatively describes regional trends. However, regional-level pipeline gas and LNG trade flows are not quantified. Moreover, broader factors affecting the evolution of natural gas trade are not explored. Shepard et al. (2022) use the MESSAGEix-GLOBIOM integrated assessment model (IAM), with pipeline and LNG trade pathways (see Table S3 for comparison of gas trade across IAMs). They explore the effects of energy trade tariff policies and a global carbon tax on overall global energy trade network characteristics (e.g., size and diversity of supply). Trade flows of coal, oil and LNG are included, but pipeline gas trade is not assessed. The models used in Feijoo et al., 2018 explicitly represent global LNG and regional pipeline trade, in competition with other energy technologies to meet multi-sectoral energy demands. However, their study focuses on North America, looking specifically at future US gas trade investments (Feijoo et al., 2018), and therefore does not analyze the evolution of LNG and pipeline gas trade flows globally. Similarly, many natural gas trade studies have largely focused on within-country or within-continental region trade (e.g., Paltsev, 2014; Zhang et al., 2016; Feijoo et al., 2016; Pedersen et al., 2022; Lau et al., 2022; Mannhardt et al., 2023). As a result, the global trade dynamics of LNG and pipeline gas, under a wide range of scenarios remains underexplored.

3.2 Methodology

3.2.1 GCAM assumptions

Our work aims to contribute to recent advances in the representation of natural gas trade in the multi-sectoral modeling literature space. We explicitly represent LNG and pipeline gas as separate trade pathways in the Global Change Analysis Model (GCAM) version 6, and further quantify future investment levels in both. GCAM v5.4 is calibrated to a 2015 base year and solves for commodity prices in each five-year time step through 2100 such that supply and demand are in equilibrium in all energy, agriculture, and water markets.

Each region's natural gas demand is met by either domestically produced or imported gas, enabling the tracking of gross imports and exports of natural gas across regions. LNG is traded in a single, global market, similar to other fossil fuel or agricultural commodities. Pipeline gas is traded in six regional pipeline blocs (**Figure 3-1**). — North America (NA), Latin America (LAC), Europe (EUR), Russia+ (RUS), Africa and Middle East (Afr_MidE), and Asia-Pacific (PAC)— consistent with current trade flows (BP, 2022; UN, 2022).

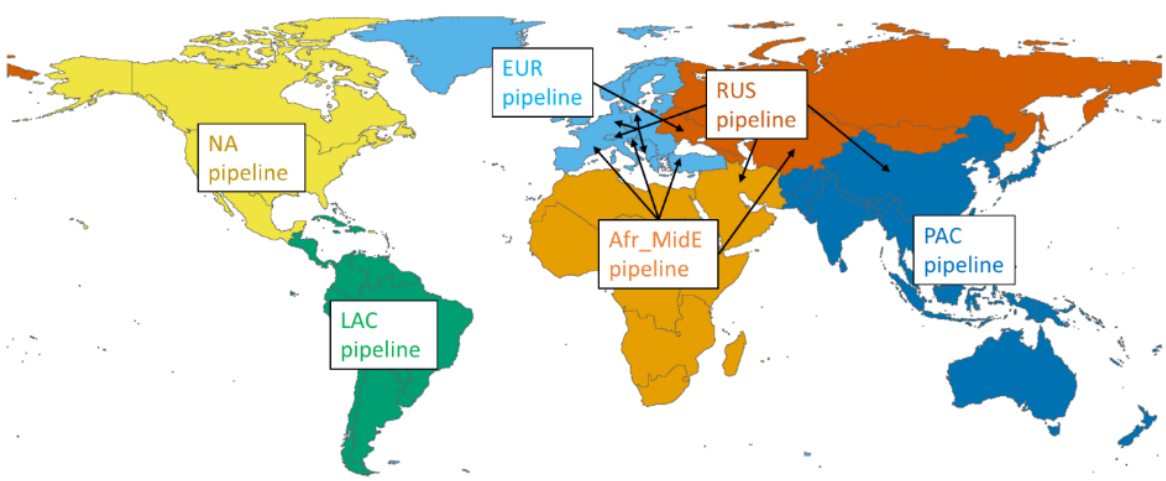

Figure 3-1. Pipeline network blocs. Regions shown with the same color form a "pipeline network bloc", and trade pipeline gas among themselves. In addition, some regions may also import gas from additional bloc(s), as shown with arrows. These trade patterns are consistent

with current trade flows (BP, 2022; UN, 2022). A full table of which regions can import from/export to each pipeline network bloc is shown in **Table B-4**.

Natural gas production potentials and costs are derived from Rogner (1997) graded resource supply cost curves (Rogner et al., 1997). Production is modeled using a resource-reserve model (Edmonds et al., 2020). Reserves are a subset of resources that can be extracted at current prices with currently available technologies. Reserves are taken out of the resource pool and production occurs from these reserves alone over their lifetime as long as prices remain above production costs. Additional reserves are converted from resources when prices are sufficiently high. Natural gas production prices are also calibrated by region in the base year.

Global fossil fuel trade (including coal, oil, and natural gas) is modeled with the Armington approach (Armington, 1969), in which each region consumes fossil energy supplies from a mix of domestic and imported supplies (which are imported from a single, global market). In this study, each region's imported natural gas is further divided into imported LNG and imported pipeline gas. Imported LNG comes from the global market for traded LNG, which can in turn be exported from any GCAM region. On the other hand, imported pipeline gas may only be supplied by the regional pipeline network bloc(s) that a given region belongs to (see **Figure 3-1**). Some regions may import from multiple pipeline network blocs, based on historically observed trade flows (see description of Comtrade data below). For simplicity, each region only exports to one pipeline network bloc.

Historical natural gas trade is calibrated to UN Comtrade data for the 2015 base year (UN, 2022). The Comtrade data set used contains volumetric data on bi-lateral trade of natural gas, via pipeline and LNG, for exporter/importer country pairs. This data is aggregated to GCAM's 32 energy-economic regions, with intra-regional trade (i.e., trade between countries within a GCAM region) excluded. Due to a known gap in Comtrade data in not including natural gas imports from Russia to Germany (when in fact, this trade flow has been significant), we have added supplementary data from Eurostat, which includes natural gas imports for Germany and Poland. Total gas trade is adjusted to maintain GCAM's global energy balances (calibrated based on the International Energy Agency (IEA)'s Energy Balances data set); in other words, gross Comtrade flows are adjusted to realize net trade consistent with natural gas production and consumption (and implicit net trade) data from the IEA (IEA, 2019). Further adjustments are made to ensure that annual energy flows are balanced for (1) total natural gas imports and exports (across pipeline and LNG carriers) in each region; (2) pipeline exports and imports for each of the six regional pipeline network blocs shown in **Figure 3-1**; and (3) LNG imports and exports globally. By assumption, all exports from a region go into its primary regional pipeline network bloc, but regions are allowed to import from multiple regional pipeline network blocs if such trade flows are present in the historical data. In the future, pipeline trade relationships are limited to those established historically – the model structure does not allow new pipeline export/import relationships to develop. All regions are allowed to trade natural gas via LNG in the future. We make additional adjustments in the USA region to account for the fact that the USA has become a net gas exporter since 2015, our calibrated base year. We additionally reduce the future growth expectations in the USA for imported natural gas.

GCAM uses a logit choice formulation to determine the shares between domestic versus international natural gas consumption, as well as between pipeline and LNG trade. Preference parameters determine how the competition between domestic versus imported natural gas, as well as between pipeline gas versus LNG trade will evolve from historical patterns. We have set parameters to decrease the preference bias for domestic gas over time, in line with expectations of increasing global market integration. We further parametrize LNG to increase more rapidly in line with recent pipeline and LNG capacity trends showing that LNG capacity is likely to become increasingly dominant in the coming decades.

Trade infrastructure (both pipeline and LNG) are represented as vintaged capacities. Liquefaction, shipping, and regasification costs for LNG capacity and pipeline costs for pipeline gas capacity are shown in **Tables B-5** and **B-6** in the SI.

All scenarios in this paper use default GCAM socioeconomic assumptions, based on SSP2 pathways (**Tables B-8** and **B-9**). Within each GCAM region, natural gas is demanded in several energy transformation and end-use sectors. Energy transformation sectors include electricity, gas-to-liquids refining, hydrogen production, and district heating (in some regions). End-use sectors include buildings (including commercial and residential buildings), industry (including cement, fertilizer, and aggregate industrial sectors), and transportation (including passenger and freight road transportation). Gas is also used as a feedstock in producing fertilizer and in the aggregate industrial production sector.

3.2.2 Scenario details

Using GCAM with this new natural gas trade infrastructure capability, we explore a range of scenarios to understand how economy-wide energy system transitions, trade infrastructure costs, and trade barriers might affect the future evolution of natural gas trade (**Table 3-1**). Although a wide range of factors could affect the evolution of natural gas, we focus on the above factors since they are expected to result in different dynamics or competition between traded pipeline gas and traded LNG. We explore two alternative economy-wide energy system pathways. The Reference pathway reflects GCAM's default assumptions about the evolution of the energy system and is the counterfactual against which to compare the other scenarios. For more context, population in the Reference¬ scenario grows from 7.4 billion to 9.3 billion, GDP from $89 trillion to $206 trillion (2020$), primary energy consumption from 550 EJ to 890 EJ, electricity generation from 24,000 TWh to 60,000 TWh, and final energy consumption from 430 EJ to 660 EJ globally between 2015 and 2050. The Transition pathway entails a shift from growing fossil fuel use towards low- and no-carbon energy technologies, with a linear decline to zero energy system CO2 emissions in 2050 globally. Note that our Transition pathway does not account explicitly for countries' policy commitments. Under each of these economy-wide energy system pathways, we explore alternative assumptions about trade infrastructure costs and trade barriers. The Low Liquefaction and Shipping Cost (LLS) assumption is intended to represent the potential for more rapid advances in LNG liquefaction and shipping technology. LLS is modeled by linearly reducing the costs of liquefaction and shipping on traded LNG to half from their 2015 levels by 2050 globally (see Table S5 for details). The Limited Trade (LT) assumption is intended to represent the potential for geopolitical or energy security concerns to limit the growth of natural gas trade. LT is modeled by imposing constraints on gas imports of both traded LNG and traded pipeline gas. In gas exporting regions and developed regions that are gas importers with sufficient resources, the constraint phases out gross gas imports by 2030. In developed regions that have low natural gas resources and developing regions that are gas importers, the constraint maintains the same share of net imports in the region's total natural gas consumption throughout the century. A detailed description of the regional groupings in the LT scenarios is provided in **Table B-7**. All scenarios account for recent trends, including recent additions to LNG export capacity in major LNG exporting regions and shifts in gas trade due to the Russia-Ukraine war.

Scenario	***Economy-wide transition***	***Trade infrastructure***	***Trade barriers***
Reference	Reference evolution of the energy system	Reference assumptions about Liquefaction and Shipping Costs	Reference assumptions involving low barriers to trade
Reference_LLS	Reference evolution of the energy system	Low Liquefaction and Shipping Costs (LLS)	Reference assumptions involving low barriers to trade
Reference_LT	Reference evolution of the energy system	Reference assumptions about Liquefaction and Shipping Costs	High trade barriers resulting in limited trade (LT)
Transition	Transition to net-zero energy system	Reference assumptions about Liquefaction and Shipping Costs	Reference assumptions involving low barriers to trade
Transition_LLS	Transition to net-zero energy system	Low Liquefaction and Shipping Costs (LLS)	Reference assumptions involving low barriers to trade
Transition_LT	Transition to net-zero energy system	Reference assumptions about Liquefaction and Shipping Costs	High trade barriers resulting in limited trade (LT)

Table 3-1. Scenario design.

3.3 Results

3.2.1 Global traded natural gas grows over the coming decades

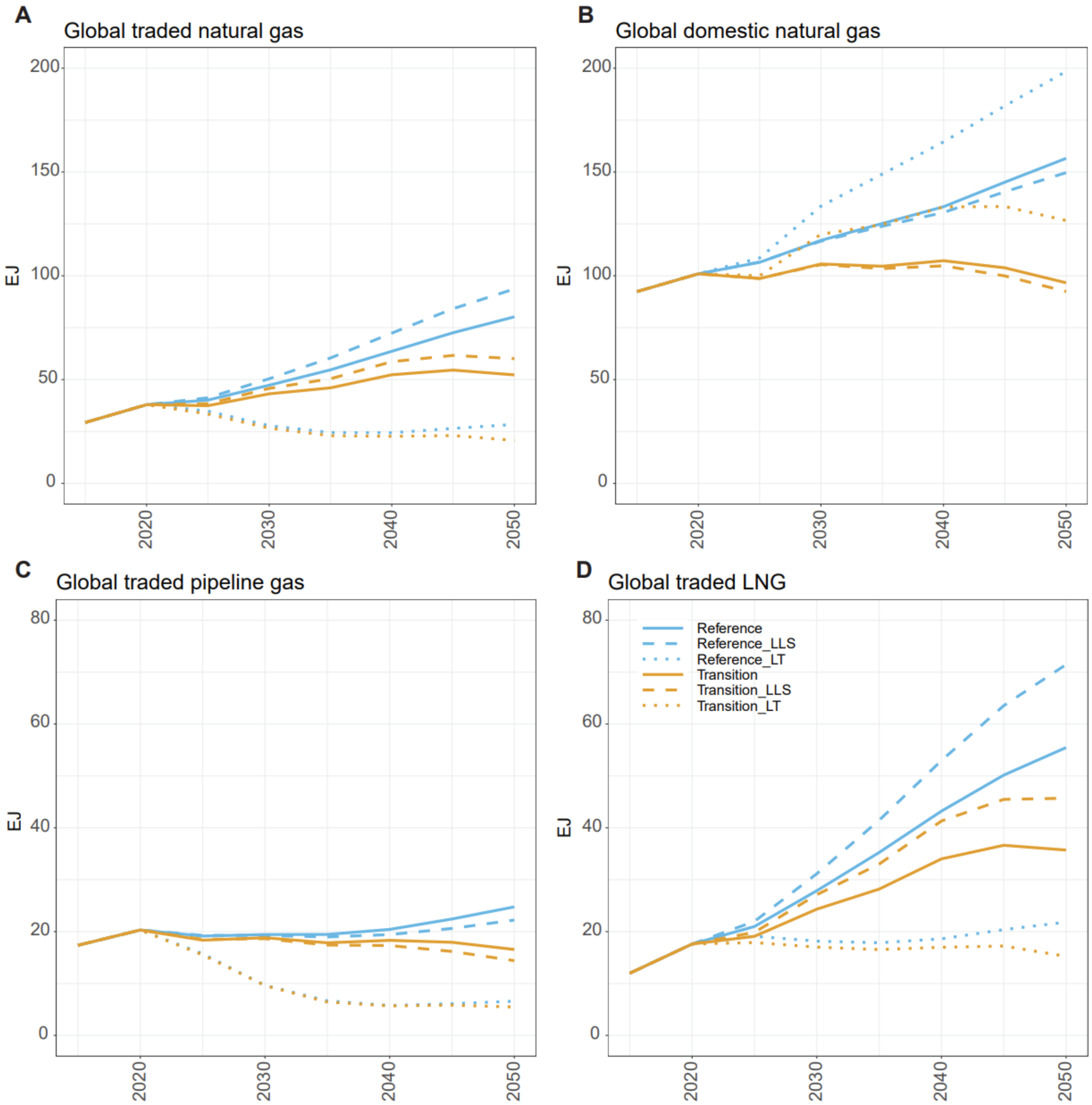

Figure 3-2. Global natural gas projections. A) traded natural gas, B) domestic natural gas (produced and consumed within the same region), C) traded pipeline natural gas, and D) traded LNG through 2050.

In most of our scenarios, globally traded gas increases by 2050 (**Figure 3-2**). In 2015, 92 EJ of natural gas was domestically produced and consumed, while 28 EJ of natural gas was traded, out of which 16 EJ was traded through pipelines and 12 EJ was traded as LNG. By 2050, under the Reference scenario, the quantity of traded LNG is larger than that of traded pipeline gas globally (55 EJ and 25 EJ, respectively). The faster growth of LNG over the coming decades reflects increasing preferences for it over pipeline gas, in line with expectations of LNG's increased dominance due to improvements in LNG infrastructure technology, allowing LNG to be shipped more widely around the world (IGU, 2023).

In the Transition scenario, traded gas is 35% lower in 2050 than in the Reference scenario, due to global energy system transitions toward lower-carbon fuels. The Low Liquefaction and Shipping Cost (LLS) assumptions result in 29% and 28% increases in LNG and 11% and 13% decreases in pipeline gas in 2050 relative to Reference and Transition, respectively. On balance, Reference_LLS and Transition_LLS increase traded gas by 17% and 15% in 2050 relative to Reference and Transition and decrease consumption of domestically produced gas by 4% and 4%, respectively.

In contrast to all other scenarios, the Limited Trade (LT) scenarios result in decreased traded natural gas by 2050, due to the import constraints in these scenarios. Under the Reference_LT and Transition_LT scenarios, traded LNG in 2050 is 61% and 57% lower than the Reference and Transition scenarios, respectively. In addition, pipeline gas in 2050 is 73% and 67% lower. In order to meet the demand for gas, Reference_LT and Transition_LT result in 27% and 31% higher domestically produced gas consumption compared to Reference and Transition, respectively.

3.2.2 Regional natural gas trade varies widely

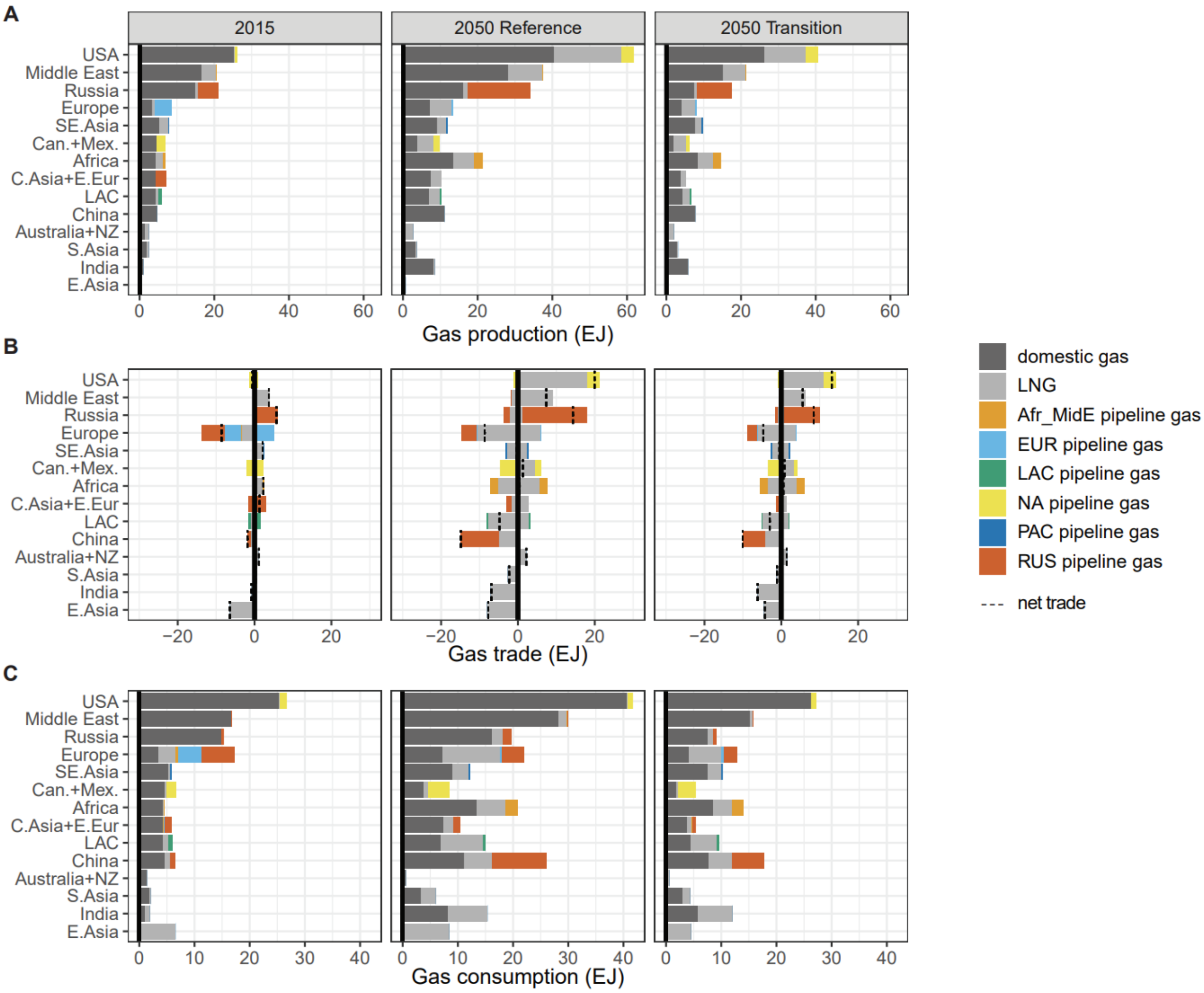

Figure 3-3. Regional natural gas projections under Reference and Transition scenarios. A) gas production, B) gas trade, and C) gas consumption across aggregated regions in 2015 and 2050 Reference and Transition. In the gas trade figure (B), gross exports are shown to the right of the y-axis, gross imports are shown to the left of the y-axis, and net trade is shown with a dashed line. For simplicity, some regions have been aggregated from multiple GCAM regions. Note that Europe includes GCAM regions: EU-12, EU-15, Europe_Non_EU, and EFTA. C. Asia + E. Eur includes GCAM regions Central Asia and Eastern Europe. See Table S10 for full aggregated region groupings.

Gas production, trade, and consumption patterns are widely different across regions and scenarios **(Figure 3-3).** Under the *Reference* and *Transition* scenarios, the USA, Middle East, and Russia are the largest natural gas producers in 2050, which is consistent with historical patterns. The USA, Middle East, and Europe were the largest natural gas consumers in 2015. By

2050, the USA and Middle East remain dominant consumers under the *Reference* and *Transition* scenarios, while China emerges as a dominant consumer. In 2050, the USA and Middle East have the largest decreases in gas consumption under *Transition* relative to *Reference* (14% and 14%, respectively). These regions have relatively lower shares of coal in their energy mix under *Reference*. China and India, regions with high shares of coal in *Reference,* experience smaller decreases in gas consumption (8.3% and 3.3%, respectively). In the *Transition* scenario, it is more economical to reduce coal consumption and continue the use of natural gas, including in combination with carbon capture and storage (CCS) in these regions **(Figure B-6).** Such transitions are consistent with previous studies (IPCC, 2022; IEA, 2023a). See **Text S1** and **Figures B9 to B-13** for detailed comparison of our results with results from the IEA World Energy Outlook and IPCC AR6 database (IEA, 2022; IEA, 2023a; Byers et al., 2022).

In 2015, pipeline natural gas exports were dominated by Russia and Europe, while pipeline imports were dominated by Europe (significant levels of inter-Europe pipeline trade). By 2050, Russia maintains the largest share of pipeline exports, but the majority of this pipeline natural gas is imported by China. This is in line with expectations of changes in Russian pipeline gas trade due to the conflict in Ukraine. In 2015, LNG exports were dominated by the Middle East, Southeast Asia, and Africa. LNG imports were dominated by East Asia and Europe. By 2050, LNG trade grows significantly across many regions. Major LNG exporters include the USA and Middle East, while major LNG importers include Europe, East Asia, LAC, and India.

While many regions focus most of their gas production on meeting domestic demand, a few net exporters export more than half of their total gas production, including Russia (53%), Canada + Mexico (61%), and Australia (83%) in the *Reference* scenario in 2050. Meanwhile, some regions are able to meet most of their demand with domestic production, but most importers import more than half of their natural gas consumption, including LAC (53%), China (57%), Europe (67%) and East Asia (96%) in the *Reference* scenario in 2050.

Major gas exporters differ in their reliance on pipelines versus LNG to export gas. For example, Russia exports 93% of its total gas exports through pipelines in 2050 *Reference,* while USA exports only 15% of its gas exports and the Middle East only 0.5% through pipelines, with the remaining share exported as LNG. Among major importers, there is also diversity in import pathways. For example, 66% of China's gas imports flow through pipelines, in contrast with 30% in Europe and 0% in E. Asia in 2050 *Reference*, with the balance of imports transported as

LNG. Overall, regional trade patterns are similar, though smaller in magnitude, under *Transition* compared to *Reference.*

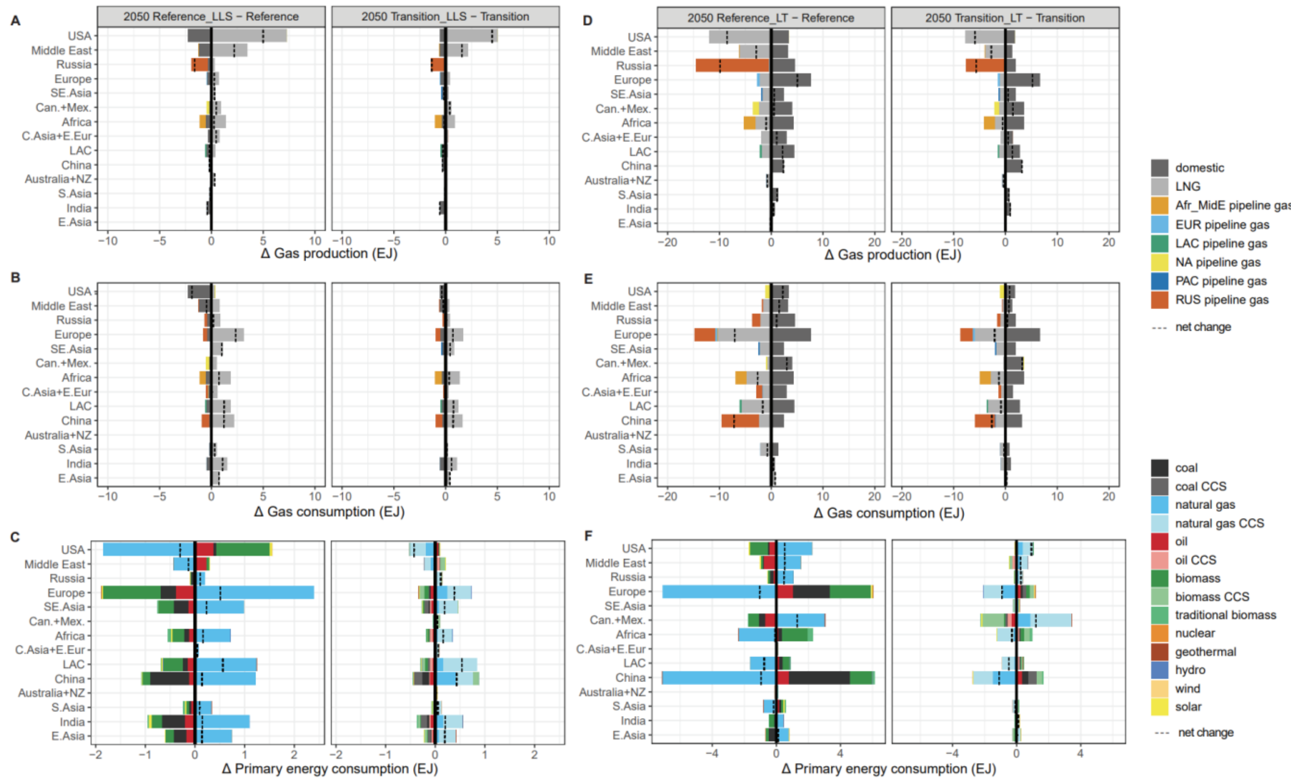

Figure 3-4. Regional projections under alternative trade patterns. A) change in gas production, B) change in gas consumption, and C) change in primary energy consumption in 2050 Low Liquefaction and Shipping Cost (LLS) scenarios. D) change in gas production, E) change in gas consumption, and F) change in primary energy consumption in 2050 Limited Trade (LT) scenarios, relative to base Reference or Transition scenarios. Net changes are shown with a dashed line. For simplicity, some regions have been aggregated from multiple GCAM regions. Note that Europe includes GCAM regions: EU-12, EU-15, Europe_Non_EU, and EFTA. C. Asia + E. Eur includes GCAM regions Central Asia and Eastern Europe. See Table S10 for full aggregated region groupings.

Across regions, Low Liquefaction and Shipping costs (LLS) increase traded LNG production and consumption, while decreasing domestic and traded pipeline gas (**Figure 3-4A** and **3-4B**). In many regions, the increase in exported LNG results in increased net natural gas production, but a few regions have decreases in gas production. For example, in Russia, a decrease of 1.5 EJ of pipeline exports outweighs an increase of 0.3 EJ of LNG exports under Reference_LLS compared to Reference in 2050. In most regions, the increase in imported LNG results in increased net natural gas consumption, which substitutes for other fuels (**Figure 3-4C**). However, a few regions, namely the USA and Middle East, have decreases in gas consumption. As LNG cost breakthroughs increase demand for exported LNG from the USA and Middle East, these regions shift some of their supplies away from meeting domestic demands to meet global demands.

Limited Trade (LT) decreases both traded LNG and pipeline gas across regions, resulting in increased consumption of domestically produced gas (**Figure 3-4D** and **3-4E**). In several major gas exporting regions, lack of trade results in less overall natural gas production. The Middle East, USA, and Russia experience respectively 8%, 14%, 29% reductions in gas production in 2050 under Reference_LT compared to Reference. Net gas exporting regions increase their gas consumption, switching away from other fuels (**Figure 3-4F**), because they have ample domestic gas resources available that they cannot export. On the other hand, net importing regions, including Europe, LAC, and several Asian regions increase domestic gas production when trade is limited. They decrease their gas consumption when trade is limited, switching mainly to bioenergy and other fossil fuels. For example, Under Reference_LT, China decreases gas consumption by 7.2 EJ (27%) relative to Reference in 2050. In Europe, gas imports are fully phased out by 2050 (a reduction of 15 EJ) and gas consumption decreases by 7.1 EJ (32%) relative to Reference. Domestic gas production increases by 7.7 EJ (106%) and 2.4 EJ (22%) respectively in Europe and China relative to Reference.

Assumptions about trade infrastructure costs and trade barriers under the Transition scenarios (Transition_LLS and Transition_LT) result in similar trends as their corresponding Reference counterparts (Reference_LLS and Reference_LT, respectively). However, changes in gas production and consumption are lower in magnitude, since less natural gas is used in the overall energy system. Additionally, under Transition scenarios, many regions switch between gas with CCS and other low-emission technologies (**Figure 3-4C** and **3-4F**). For example, in regions that increase gas consumption under Transition_LT, like the USA, Middle East and Russia, there is a shift from bioenergy with CCS, oil with CCS or renewables towards gas with CCS. On the other hand, in much of Europe and China, there is a decrease in gas CCS resulting in a shift towards biomass with CCS, coal with CCS, renewables, and other technologies.

3.2.3 Investments in natural gas trade infrastructure are needed

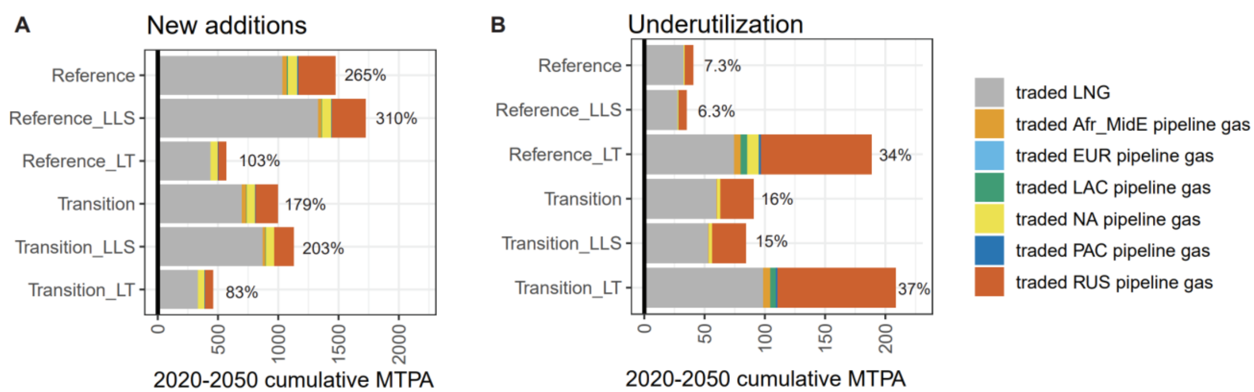

Figure 3-5. Pipeline and LNG export capacity additions and underutilization. A) 2020-2050 cumulative new export capacity additions, B) 2020-2050 cumulative export capacity underutilization. Underutilization is capacity that has already been built but is not operated at full capacity. MTPA = million tons per annum. Percentages beside each bar represent the percentage relative to 2015 capacity that the cumulative new additions or underutilization represent for each scenario. See **Figure B-3** for import capacity additions and underutilization. See **Figures B-2** and **B-4** for 2050 cumulative capacity additions and underutilizations by region.

Across scenarios, investments in new pipeline and LNG trade infrastructure are needed globally to meet increased demands (**Figure 3-5**). Between 2020 and 2050, 1470 million tons per annum (MTPA) of traded natural gas export capacity, including both pipeline and LNG infrastructure, are added in the Reference scenario. Out of the new added export capacity, 70% is new LNG infrastructure, 21% is new pipeline infrastructure in the Russia+ network, 5% is new pipeline infrastructure in the North American network, and the remaining new pipeline infrastructure comes from other pipeline networks around the world. Low Liquefaction and Shipping costs (LLS) result in additional LNG infrastructure being built over the coming decades. The Reference_LLS scenario has 297 MTPA of additional LNG export capacity added between 2020 and 2050 compared to Reference, with less new additions needed in each of the pipeline networks. The Transition and Limited Trade (LT) scenarios result in less new additions relative to Reference. The Transition and Reference_LT scenarios have 33% and 61% less additions by 2050 compared to Reference, respectively. In combination, under the Transition_LT scenario, there is 460 MTPA of new gas export capacity added between 2020 and 2050, 69% less than under the Reference scenario. For context, current global liquefaction capacity stands at 478 MTPA, while proposed aspirational liquefaction capacity (pre-decisional) is estimated at 997 MTPA (IGU, 2023).

Risks of underutilized capacity exist across scenarios, although they represent a small percentage of total capacity. The Reference scenario has 41 MTPA of cumulative underutilized natural gas export capacity between 2020 and 2050, 80% of which is underutilized LNG capacity. Transitions to a low-carbon energy system and limitation on trade result in more underutilizations overall relative to Reference, as well as higher shares of underutilized pipeline capacity. The Transition scenario has 91 MTPA of cumulative underutilized gas export capacity by 2050, 66% of which is underutilized LNG capacity and 30% of which is in the Russia+ pipeline network. The Reference_LT scenario has 189 MTPA of cumulative underutilized gas export capacity, 39% of which is underutilized LNG capacity and 49% of which is in the Russia+ pipeline network. Combined, in the Transition_LT scenario, there is 208 MTPA of cumulative underutilized gas trade capacity.

3.4 Discussion and Conclusions

This study explicitly represents LNG and pipeline gas as separate trade pathways in a state-of-the-art multi-sectoral model, quantifying the future evolution of and investment levels in each. Across our scenarios, global traded natural gas ranges between 71-319% of 2015 levels, with traded LNG ranging between 110-500% and traded pipeline gas ranging between 130-600% of their 2015 levels. Our scenarios project 460-1700 MTPA of new gas export infrastructure needed between 2020 and 2050, 70-77% of which is new LNG export infrastructure. The increased growth of traded LNG over pipeline gas reflects expectations of its increasing dominance as it can be shipped more widely around the world.

Increased natural gas trade opens opportunities to use natural gas to meet increasing demands for electricity, energy in industry and buildings, and fertilizers. However, increased natural gas trade also presents costs and potential risks in a world of shifting geopolitics and broader economy-wide transitions. Our results highlight how costs and potential risks diverge across regions based on each region’s natural gas trade status and overall energy system profile.

For importing regions, increased reliance on traded gas—particularly traded pipeline gas—and its associated trade infrastructure could represent a potential risk for economies in maintaining secure supplies of energy. Thus, many importing regions are looking at different strategies to enhance energy security (Vivoda, 2019). Advances in LNG technology, such as the reduction of liquefaction and shipping costs, could help reduce dependence on pipeline gas imports from a limited set of trade partners, allowing regions to import natural gas more flexibly from a wider set of regions. For example, Europe imports 67% of its total gas consumption—30% of which through pipeline— under a reference scenario in 2050 and reduces its pipeline import dependency to 23% under a scenario with lower liquefaction and shipping costs. As is consistent with recent strategies in Europe aiming to meet gas shortages due to ongoing geopolitical events, increased LNG trade can serve as a way to hedge against the risk of potential sudden loss of gas supply due to geopolitical events impacting pipeline trade (Mannhardt et al., 2023; IEA 2023b). However, this strategy could require significant investment in new LNG trade infrastructure (**Figure 3-5**, **Figure B-3**).

Importing regions may also meet increased energy demands with a combination of domestic gas production (in regions that have domestic resources, like Europe) and shifts to other fossil and renewable resources, as seen in our scenarios with limited trade. Alternatively, transitioning to a low-carbon energy system facilitates less demand for natural gas within each region's energy system, as regions instead switch to renewable and low-carbon fuels (IEA 2023b). However, it is important to note that importers experience different levels of gas consumption reduction. For example, under a scenario with an economy-wide transition to low-carbon fuels, China reduces gas consumption by 8.3% relative to a reference scenario by 2050. However, Europe reduces gas consumption by 14%. This finding is consistent with regional differences in gas consumption reduction in the literature, e.g., between IEA's STEPS and APS scenarios (**Figure B-11**; IEA, 2022).

Overall, transitions to low-carbon energy systems globally result in less gas trade and less need for gas trade infrastructure. For example, our Transition scenario results in 33% less cumulative new additions in natural gas export capacity globally by 2050. These transitions could thus also reduce dependence on gas imports, which in some cases, could improve energy security (Jewell et al., 2016). In our study, the combination of transitioning to a low carbon energy system and limited trade results in the lowest level of new natural gas trade capacity additions across scenarios explored in this study. While risks of underutilized capacity might increase under transitions to low-carbon energy systems, natural gas with CCS technologies can potentially mitigate this risk, by maintaining some demand for natural gas (Feijoo et al., 2018).

For net exporting regions, the implications of shifting trade patterns— due to technological advancements in LNG or geopolitical shifts— depend on whether the region largely produces gas for exports versus for the domestic market, and whether the region largely exports via pipeline or LNG. For example, Russia, which exports 53% of its gas production (93% of which through pipelines) in 2050 under a reference scenario, experiences 2% and 29% declines in production respectively under low liquefaction and shipping cost and limited trade assumptions, respectively. Thus, regions which largely produce gas for exports, and largely export through pipelines, may experience larger production losses as a result of advances in LNG liquefaction and shipping technology, or due to geopolitical shifts that disrupt trade. Recent geopolitical events resulting in Russia's diminished trade position highlight the risks of its historical dependence on pipeline exports (IEA, 2022).

On the other hand, regions such as the USA or Middle East, which largely produce for the domestic market with a relatively smaller share of exports and have a larger share of exported LNG as compared to exported pipeline gas experience do not experience production losses due low liquefaction and shipping costs, and experience relatively smaller declines in production due to limited trade relative to a reference scenario (14% and 8%, respectively) compared to Russia. Nevertheless, all exporters also face particular risks associated with increasing trade infrastructure. For LNG exporters, new capital infrastructure can pose a significant cost, as the liquefaction plants required at export terminals are much more capital intensive and take much longer to build than the required infrastructure (storage and regasification plants) on the import side (Paltsev, 2015).

3.5 Limitations and Future work

This work opens several avenues of future research. Foremost, future work might explore the uncertainty around the costs of pipeline and LNG infrastructure, and the costs of natural gas transport. Further research could look into the regional economic implications of natural gas trade expansion or limitation, taking into account recent regional investments in natural gas trade infrastructure. The modeling capability developed in this study also lends itself to research on implications of alternative energy futures for investments, underutilization, and premature retirements of natural gas trade infrastructure, as has been done in the power sector (Binsted et al., 2020; Iyer et al., 2015).

This study has focused on a few initial exploratory factors. Several other factors, in addition to and in combination with the factors chosen here could yield different future pathways for pipeline gas and LNG. In particular, this study does not evaluate how assumptions (e.g., costs, rates of technological change in the future) on different technologies that rely on natural gas could influence the future growth of LNG and pipeline natural gas. Despite being a fossil fuel, natural gas could play specific key roles in transitions to overall lower carbon energy systems, thus resulting in overall reductions in global CO_2 emissions. For example, for regions pursuing stringent climate mitigation (or aiming to meet high levels of energy supply domestically), high levels of solar and wind electricity generation could require increased levels of natural gas generation serving as backup generation (Bistline & Young, 2022), and thus serve a key role in enhancing climate resilience. Similarly, the availability of carbon dioxide removal, including CCS, could be an important sensitivity in affecting demands for natural gas (Jordaan et al., 2022). Regional supply and demand profiles for natural gas, due to these interacting technologies, will affect where LNG versus pipeline gas is deployed. A key caveat here is that demand sectors represented here do not differentiate natural gas from LNG versus pipeline gas, but future work could disaggregate this.

Additional work can also use the trade structure developed here to better understand regional costs and emissions associated with the trade of natural gas. Our study does not include infrastructure requirements for internal transportation of gas within GCAM regions. Our study does not include energy penalties associated with liquefaction, regasification, and shipping, which would be helpful in further comparing the trade of natural gas with the trade of other energy commodities. These limitations can be considered for future work.

4. Essay 3: Emissions leakage and economic losses could limit the effectiveness of deforestation-linked oil crop import restrictions

This essay is based on: Yarlagadda, B., X. Zhao, G. Iyer, T. Wild, N. Hultman, and J. Lamontagne (submitted). Emissions leakage and economic losses could limit the effectiveness of deforestation-linked oil crop import restrictions.

4.1 Introduction

In accordance with Paris Agreement goals of limiting warming to below 1.5-2°C, countries are individually responsible for meeting their nationally determined contributions (NDCs) and long-term strategies. At the same time, each country's economy is linked to others through international trade. Therefore, trade policies are increasingly being considered as part of emissions reduction strategies (Burney et al., 2021). Meanwhile, targets to combat emissions from land use sectors are gaining traction. The Glasgow Leaders' Declaration on Forests and Land Use was signed by 145 countries at COP26 in 2021 committing to halt and reverse deforestation and land degradation by 2030 (The National Archives, 2021). COP28 in 2023 saw countries strengthening this commitment. Nevertheless, halting deforestation has remained a major policy gap towards achieving Paris Agreement goals, with deforestation continuing to increase in recent years (Iyer et al., 2023).

The production of globally traded 'forest-risk commodities' is the largest driver of tropical deforestation (Curtis et al., 2018; Pendrill et al., 2019). To combat this, a number of zero-deforestation commitments (ZDCs) have been initiated, ranging from voluntary actions in the private sector (e.g., certification standards and moratoria; Lambin et al., 2018; Gibbs et al., 2015) to government-led import restrictions. Import restrictions have been proposed in several countries, e.g., US (Schatz, 2021) and UK (McGrath, 2020), but EU policies have been the most extensive in this regard. As of 2023, the EU's deforestation regulation prevents imports into the EU of seven commodities produced on post-2020 deforested land: cattle, cocoa, coffee, oil palm, rubber, soy, and wood, as well as products derived from these commodities (EU, 2023). As of 2022, both palm and soybean oil have been designated as high induced land-use change (ILUC) biofuels, and the EU has also set targets to phase out the use of these high ILUC biofuels by 2030 (EU, 2022). Oil palm and soybean commodities have the potential to be substituted with other oil crops (particularly for bioenergy), as well as a range of other agricultural crops for use in food, non-food, and animal feed.

However, open questions remain regarding 1) the effectiveness of import-side restrictions in reducing deforestation, and 2) the economic implications of such restrictions on producers and consumers. Private sector initiatives have faced challenges due to leakage to other commodities or regions, lack of transparency and traceability, and smallholder marginalization (Lambin et al., 2018; DeFries et al., 2017; RSPO, 2020). The EU's deforestation regulation could face similar issues. Meanwhile, EU's deforestation and biofuel regulations have been criticized by exporter countries in the Global South and have been brought forward to the World Trade Organization (WTO) for arbitration on grounds of discrimination (WTO, 2022). Exporter countries are concerned that such regulations will have severe economic consequences for producers, particularly smallholders, and will hinder progress on sustainable development goals (Lambin et al., 2018; Marques da Silva, 2023; Mano, 2023; The Straits Times, 2023). Moreover, exporter countries allege that such deforestation regulations are a pretext for protectionism, e.g., favoring EU-grown oil crops (e.g., rapeseed and sunflower oil) over imported oil crops like oil palm and soy (Mano, 2023; Reuters, 2019).

Several impact assessments of EU's deforestation regulations (Bougas et al., 2023; IDH, 2020; Heflich, 2020; COWI, 2018; Cuypers et al., 2013) have been conducted (**Table C-1**). However, these assessments rely on simplified assumptions on commodity demand growth rates, and deforestation and LUC emission intensities. Moreover, these assessments do not account for demand changes in other regions, interactions between competing land uses, or the potential for emissions leakage. Meanwhile, several global economic modeling studies (**Table C-2;** Villoria et al., 2022; Busch et al., 2022; Taheripour et al., 2019; Leijten et al., 2023; Delzeit et al., 2021; Valin et al., 2015) have dynamically evaluated impacts of either palm or soy trade restrictions individually on land use change and LUC emissions, especially in key export producer regions. Studies have highlighted the potential for local leakage within a region when ZDCs cover a limited area (Villoria et al., 2015) and assessed the upper extent to which LUC emissions could be reduced if ZDCs are fully adopted globally (Villoria et al., 2022; Leijten et al., 2023). However, the extent to which global leakage could dilute the effectiveness of import restrictions has not been quantified. Many studies, including those evaluating economic impacts (Taheripour et al., 2019), have represented palm or soy demand in a historical counterfactual context (Villoria et al., 2022; Busch et al., 2022; Taheripour et al., 2019), not accounting for changes in future demands. Therefore, no studies have quantified future economic implications of import restrictions. No studies have explored the role of import restrictions as a potential climate policy mechanism within the context of countries' emissions reduction commitments. We address these gaps by quantifying the extent to which import restrictions on oil palm and soybean (as currently structured or with potential extensions) could reduce future deforestation and LUC emissions and their broader economic impacts in key oil crop producing and consuming regions. See Appendix C.1 for additional details.

4.2 Methodology

4.2.1 GCAM assumptions

The version of the model used here is based on GCAM 7, calibrated to a 2015 base year. For this study, we implemented a new logit-based Armington bilateral trade framework **(Figure C-1)** within GCAM to track the source and destination of oil palm and soybean crops. All other agricultural crops are modeled with an Armington global pool trade approach (Zhao et al., 2022), in which each region consumes agricultural commodities from a mix of domestic and imported supplies (imported from a single global market). Both bilateral trade (for oil palm and soy crops) and gross trade (for all other crops) are calibrated to FAO data in 2015. Bilateral trade for oil palm and soy crops implies that the same pattern of trade between regions that existed in 2015 will hold in future periods (except for when specific routes are restricted by our import restrictions).

4.2.2 Scenario details

We explore a series of scenarios representing varying levels of import restrictions on oil palm and soy from deforesting regions through 2050 (**Table 4-1**; Appendix C.2). Our base scenario (*REF*) includes no import restrictions and represents a scenario consistent with achieving 2°C through carbon prices on fossil fuel and industrial (FFI) sectors but not on LUC sectors. The *REF* scenario is consistent with limiting warming to 2°C by 2100. This scenario includes emission constraints on FFI emissions for each GCAM region, consistent with "NDC++" pathways in Iyer et al. (2022). Further, we included a global bioenergy constraint, limiting 1st and 2nd generation bioenergy to less than 33.4 EJ in 2020, increasing linearly to 58.4 EJ in 2050, and 100 EJ in 2100. We include no emission constraints or carbon prices on land sectors. We use SSP2 socioeconomic assumptions.

The import restriction scenarios were modeled by including import constraints between source and destination markets for oil palm and soybean trade. Restricted export markets were defined as regions deforesting between 2015-2050 in the *REF* scenario (see **Figure C-3**). The *EU freeze* scenario imposes a ceiling on EU imports of oil palm and soy products from deforesting regions at 2020 levels in all future periods, consistent with currently enacted regulations prohibiting imports of commodities linked to post-2020 deforested land (EU, 2023). The *HighInc freeze* scenario extends these import restrictions to all high-income GCAM regions, thus representing an extension in which similar high-income countries follow EU's lead. Alternatively, the E*U/Top 5 freeze* scenario represents an extension in which import restrictions are imposed by EU and the top 5 net importing GCAM regions for oil palm and soy respectively, many of which are emerging economies projected to face increased oil crop demands in the coming decades. The *EU ban* scenario, in which the EU fully bans all imports of oil palm and soy from deforesting regions, represents a potential extension of EU's high ILUC biofuel phaseout policy (EU, 2022).

Finally, a counterfactual *Land protect* scenario protects additional forest land in each deforesting region equivalent to land reduced from oil palm and soy production in the *HighInc freeze* scenario compared to *REF*. This scenario enables a comparison of the economic and emissions implications of directly protecting forest land versus indirectly via import restrictions. The *Land protect* scenario was modeled by calculating the reduction in oil palm or soybean land in each deforesting (export-restricted) region under the *HighInc freeze* scenario. This value was added to forest land value in the *REF* scenario in each region to form a set of explicit land protection constraints for each deforesting region from 2025 to 2050.

Scenario	Policy	Import restricting regions
REF	None	None
EU freeze	Ceiling on imports from deforesting regions at 2020 levels	EU
HighInc freeze	Ceiling on imports from deforesting regions at 2020 levels	EU, rest of Europe (EFTA and Europe_Non_EU), Argentina, Australia_NZ, Brazil, Canada, China, Japan, Mexico, Middle East, Russia, South Korea, Taiwan, USA

EU/Top 5 freeze	Ceiling on imports from deforesting regions at 2020 levels	EU and top 5 net importers for oil palm and soy: For oil palm: EU, India, China, Pakistan, Middle East, Australia_NZ For soybean: EU, China, rest of Southeast Asia, Middle East, Africa_Northern, Indonesia
EU ban	Full ban on imports from deforesting regions	EU
Land protect	Protect forest land in each deforesting region equivalent to land reduced from oil palm and soy production in *HighInc freeze – REF*	None

Table 4-1. Scenario design. 'Deforesting regions' are defined as regions deforesting in *REF* between 2015 and 2050 (see **Appendix C.2; Figure C-3** for details).

4.3 Results

4.3.1 Production and consumption shifts resulting from import restrictions

Oil palm and soy have different market characteristics. While oil palm can only be grown in tropical climates, soybeans can grow in both tropical and temperate climates. 57% and 32% of global oil palm in 2015 were produced in Indonesia and the rest of Southeast Asia (RO SEAsia)[1], respectively **(Figure 4-1)**, both of which have been undergoing deforestation. Meanwhile, soybean production in 2015 was split largely between Brazil (30%) and Argentina (17%), which have been undergoing deforestation, and the USA (34%), which has not.

Under the *EU freeze* scenario, there are negligible changes in oil palm and soybean production. This is because the EU alone makes up a small fraction of global palm and soy import demand. In the absence of import restrictions (under the *REF* scenario), EU experiences smaller increases in soy demand relative to other regions and sees decreases in oil palm demand by 2050 relative to 2020 levels (**Table C-3**).

Under the *HighInc freeze*, *EU/Top 5 freeze* and *EU ban* scenarios, key deforesting oil crop exporters— Indonesia, RO SEAsia, Brazil, and Argentina— experience declines in oil palm or soy production. Across these extended import restriction scenarios, Indonesia and RO SEAsia face net decreases of 1.8-6.3% and 6.0-13%, respectively, in oil palm production relative to *REF* in 2050. Brazil and Argentina face net decreases of 5.3-22% and 2.5-7.9%, respectively, in

[1]In GCAM, Malaysia is contained within the rest of Southeast Asia region (referred to in paper as RO SEAsia). Indonesia is represented as a standalone GCAM region.

soybean production relative to *REF* in 2050. Indonesia's relatively smaller declines due to import restrictions are because of the larger share of its production supplied to domestic markets. Brazil's relatively larger declines under the *HighInc freeze* and *EU/Top 5 freeze* scenarios are due to the large share of its production that would otherwise be exported to a single import-restricting country, China. In contrast, other major deforestation-linked exporters have a relatively more diversified set of export markets, including markets not enacting import restrictions.

Despite the overall net reductions in total oil palm and soybean production in key deforestation-linked exporting regions, there is some market-switching leakage, as exporters increase exports to unrestricted markets and/or increases in domestic consumption. A market-switching leakage rate can be calculated for deforestation-linked producer regions (see **Equation 3** in Appendix C2.4). This market-switching leakage rate ranges between 8.2-13% and 8.2-13% across extended import restriction scenarios for oil palm in Indonesia and RO SEAsia, respectively, and 10-65% and 17-64% for Brazil and Argentina, respectively in 2050. This leakage rate is particularly high for Brazil and Argentina under the *EU ban* scenario, as they can divert significant soy production to China and the rest of the world. In addition, across scenarios, import-restricting regions also shift to meet some of their demand domestically or from unrestricted exporters. In particular, the USA increases in soy production between 3.4-5.4% across extended import restriction scenarios relative to *REF* in 2050.

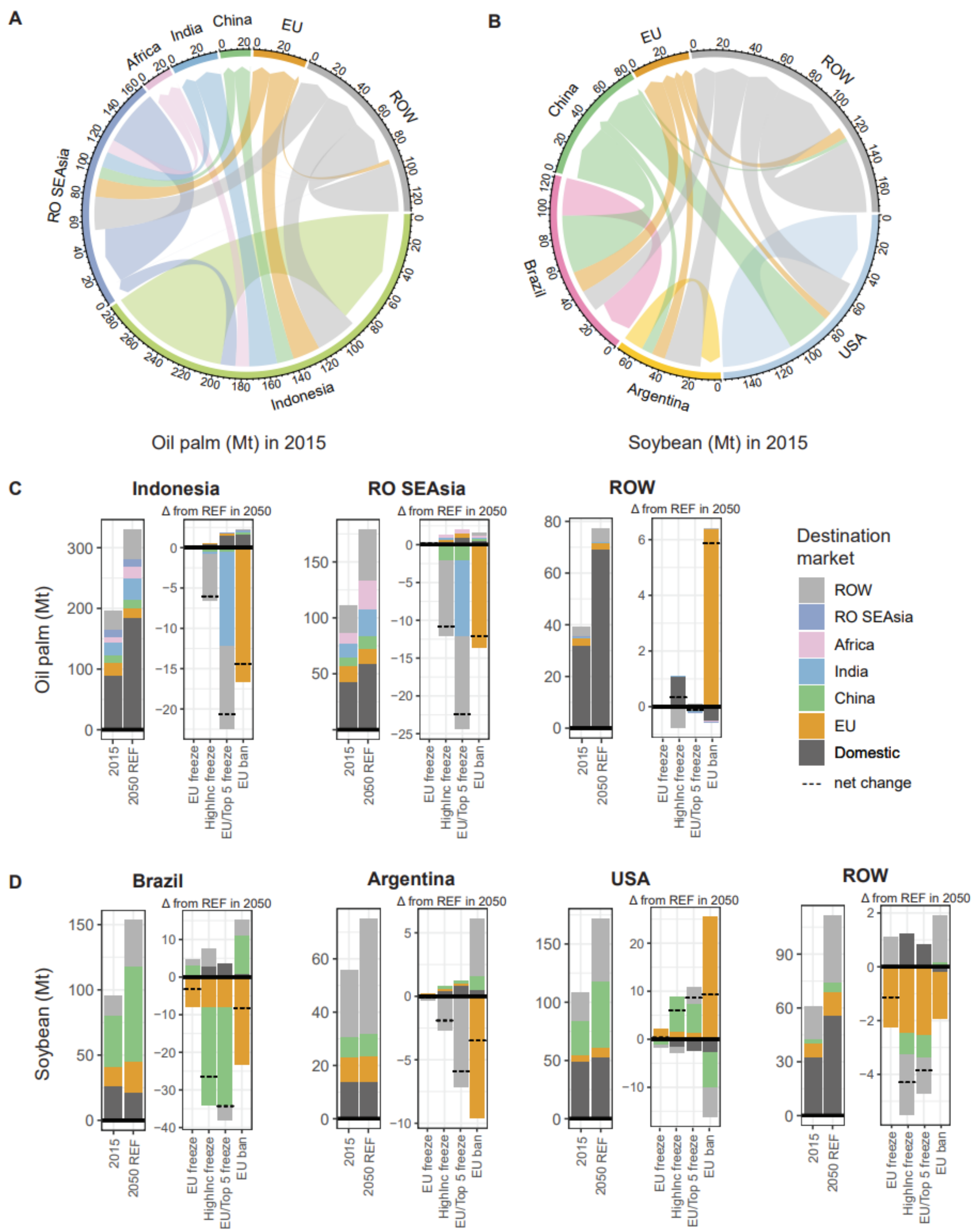

Figure 4-1. Oil palm and soybean production (domestic and bilaterally traded flows**).** A) oil palm and B) soybean production volumes in 2015 (million tons). C) oil palm and D) soybean production volumes by region across scenarios (million tons). The left panel for each region shows total production in 2015 and 2050 *REF* and the right panel for each region shows the

change in production between each import restriction scenario and *REF* in 2050. Domestic production volumes are consumed within the indicated producing region. 2030 results shown in **Figure C-4**.

4.3.2 Land-use and emissions implications of import restrictions

In Indonesia, RO SEAsia, Brazil, and Argentina, the *EU freeze* scenario results in negligible changes in land use across regions, but extended import restrictions could reduce deforestation **(Figure 4-2)**. In the extended import restrictions scenarios, forest land replaces some of the land used to grow oil palm or soybean crops under *REF* and as a result, reduces LUC emissions in these four key exporter regions relative to *REF* **(Figure 4-3).**

However, a majority of the land saved from growing oil palm or soy is allocated to other land types, including other crops and pasture, representing another key mechanism of emissions leakage. See detailed demand substitution by sector in **Figures C-6 to C-9**. A land use-switching leakage rate can be calculated for deforestation-linked producer regions (see **Equation 4** in Appendix C2.4). Across extended import restriction scenarios in 2050, this land use-switching leakage rate ranges between 94-96% and 77-79% for soy in Argentina and Brazil, respectively, and 55-68% and 20-78% for oil palm in Indonesia and RO SEAsia. In addition, other regions also compensate for the import restrictions, e.g., the USA increases land for soy production and several regions increase land for other crop production. As a result, several regions have less afforestation and consequently, higher LUC emissions.

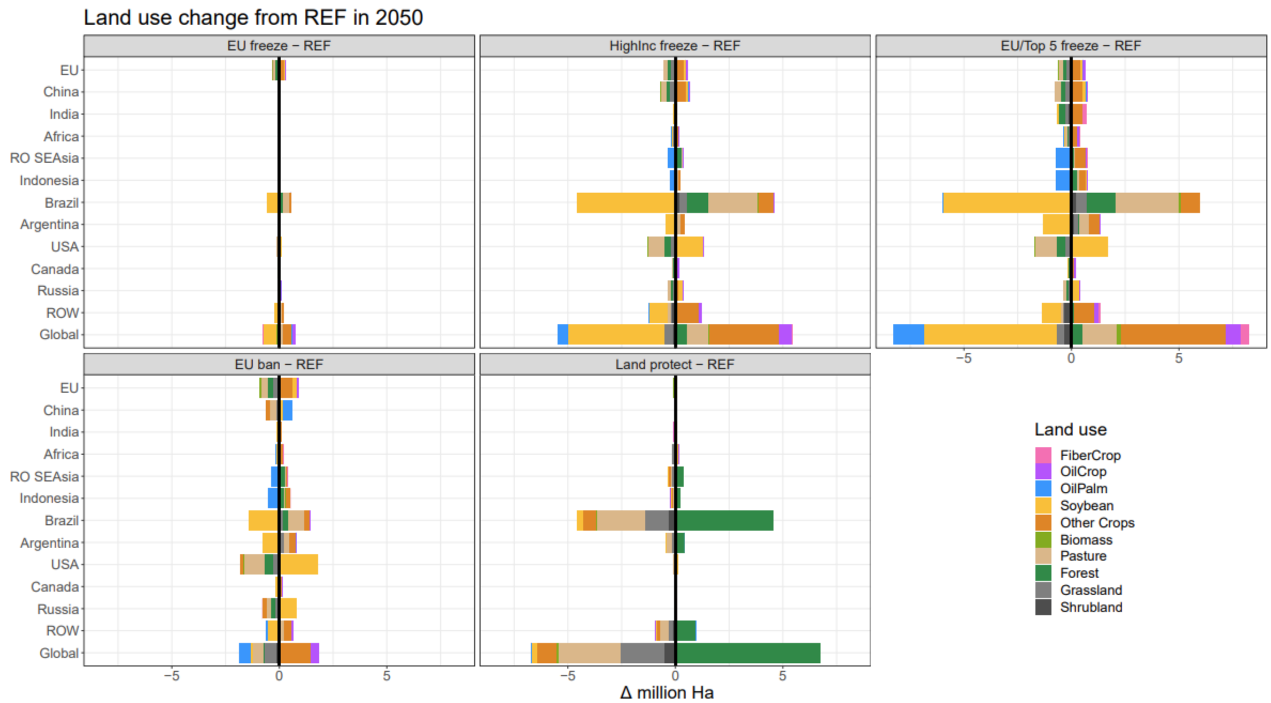

Figure 4-2. Land use change. The panels show changes in land use across scenarios relative to *REF* in 2050 (million Ha). 2030 results shown in **Figure C-5**.

A key insight from our study is that import restrictions might have negligible impacts if imposed by EU alone but could achieve larger emissions reductions in key deforesting regions if imposed more broadly **(Figure 4-3).** For example, Brazil achieves 210 MtCO2 (5.1%) and 280 MtCO2 (6.7%) reductions in cumulative LUC emissions between 2025-2050 relative to *REF* under the *HighInc* freeze and *EU/Top 5 freeze* scenarios, respectively. However, globally, impacts across import restriction cases remain small due to emissions leakage. The *HighInc freeze* and *EU/Top 5 freeze* cases achieve 134 MtCO2 (0.5%) and 165 MtCO2 (0.6%) reductions in global cumulative LUC emissions between 2025-2050 relative to *REF*.

As a point of comparison, we show LUC and LUC emissions implications in our *Land protect* scenario. This direct forest protection scenario achieves larger reductions in cumulative LUC emissions compared to all import restriction scenarios globally, and in nearly all cases for the key deforestation-linked export regions. Directly protecting forest land is more effective than indirect protection via import restrictions because land-switching leakage rates under import restriction scenarios are high.

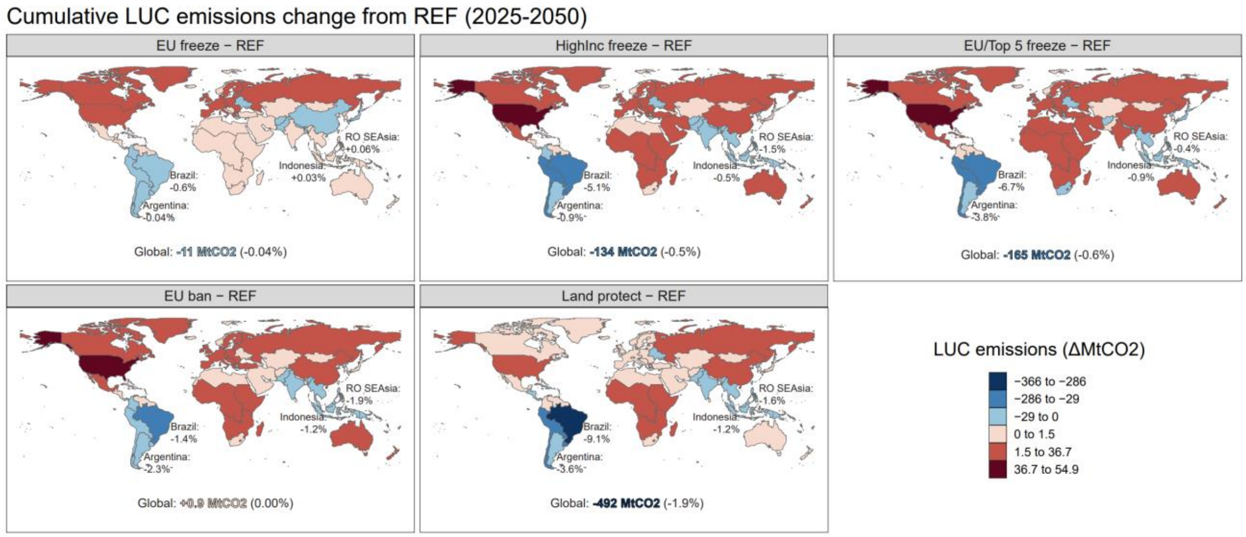

Figure 4-3. Land use change (LUC) emissions. The maps show cumulative LUC emissions (2025-2050) across GCAM regions across scenarios relative to *REF* (MtCO2). % changes in cumulative LUC emissions (2025-2050) for the key deforesting oil crop exporting regions (Brazil, Argentina, Indonesia, and RO SEAsia) are indicated in each figure. % changes in cumulative LUC emissions through 2075 and 2100 are shown in **Table C-4**.

4.3.3 Economic implications of import restrictions

Major oil crop exporters subject to import restrictions (Brazil, Argentina, Indonesia, and RO SEAsia) may experience losses in oil crop production revenue, mediated only slightly by substitution to producing other agricultural commodities **(Figure 4-4).** Under the *EU freeze* scenario, Brazil and Argentina experience losses of $6.0 billion and $0.8 billion (in 2020$) in cumulative primary agricultural production revenue relative to *REF* by 2050, while Indonesia and RO SEAsia do not experience losses. Under extended import restrictions, Brazil, Argentina, Indonesia, and RO SEAsia experience losses of $19-61 billion, $4.1-15 billion, $4.1-12 billion, and $4.6-9.3 billion in cumulative primary agricultural production revenue relative to *REF* by 2050.

Meanwhile, substitute producer regions like the USA and import regions like EU, China, and India receive increases in production revenue (in at least some extended import restriction scenarios) as they substitute oil crop production (oil palm, soy, or rapeseed or sunflower crops), or other crops more generally. EU oil crop producers receive increases in cumulative oil crop production revenue between $2.6-16 billion as a result of import restrictions.

However, importers also face significant increases in cumulative total primary agricultural expenditures relative to *REF* by 2050. For example, EU faces increases of $37 billion under *EU ban*, while China and India face increases of $46-49 billion and $33 billion, respectively, when they are part of the set of regions enacting import restrictions. Such increases in primary agricultural expenditures would hurt consumers and could cause food security concerns, particularly for developing regions. These results highlight why developing regions, like India, which are major consumers of imported oil crops, may be unlikely to follow EU's suit in imposing import restrictions, and therefore why the *EU/Top 5 freeze* scenario could be considered a less plausible extension than the *HighInc* freeze scenario. In contrast to import restriction scenarios, the direct *Land Protect* scenario has minimal economic impact changes relative to *REF* (see Appendix C.2.3 for additional discussion on *Land Protect*).

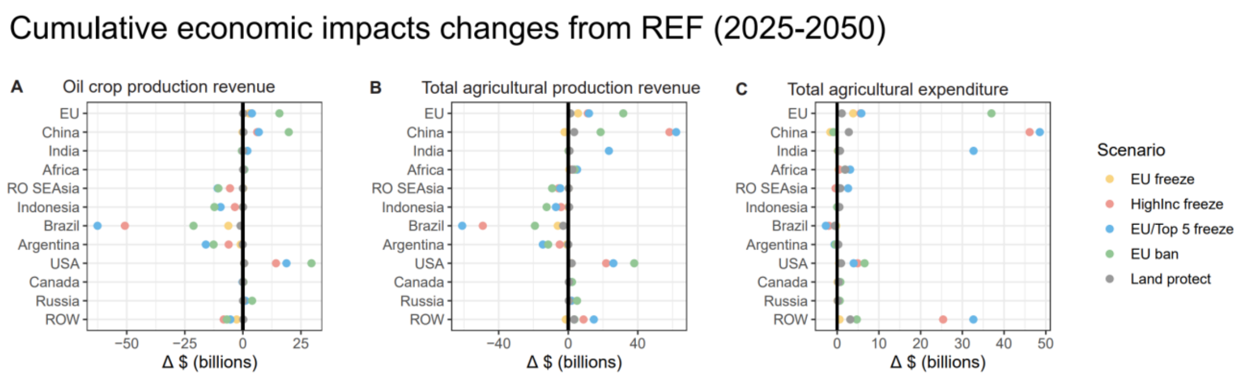

Figure 4-4. Economic impacts. Change in a) oil crop production revenue, b) total primary agricultural revenue, c) total primary agricultural expenditures across scenarios relative to *REF*, cumulative from 2025-2050 (in billions 2020$).

4.4 Discussion and Conclusions

In this study, we assess how multiple mechanisms of leakage across the agricultural production supply chain could dilute the effectiveness of import restriction policies, thus lowering their LUC emissions reductions. When faced with trade restrictions on their products, producers could instead sell commodities in non-restricted markets (to other international importers or in domestic markets). Meanwhile, production of oil crops or other substitute crops could spill over to other regions. Only a fraction of the land saved from crop production may be forested, as producers can switch to other agricultural commodities entirely (those not covered under import restrictions), or allocate lands to other uses (which could have lower land carbon than forests).We find that leakage at the end stages of the supply chain, i.e. leakage of oil palm or soy production to other markets is lower than at the early stages of the supply chain, i.e. leakage of land allocation to other crops or uses entirely. This is reflected in the fact that land-switching leakage rates are higher than market-switching leakage rates across key deforesting-linked producing regions.

Our results highlight that currently enacted deforestation regulations in the EU alone are unlikely to have a significant impact on global oil palm or soy trade flows, land use changes, emissions, or economic impacts. Yet, our results highlight that even if the EU were to fully ban imports of oil palm and soy across all producers within countries undergoing deforestation, as in the *EU ban* case, the impact on reducing global LUC emissions would still be minimal. This is because EU alone represents a small and diminishing share of global demand for oil palm and soy commodities. Nevertheless, EU's deforestation regulations could play an important role in setting global standards for other regions to follow. Additionally, these policies can enable a more level-playing field for companies pursuing sustainable production practices (EUR-Lex, 2021).

If extended beyond the EU, import restrictions could still have a limited impact in reducing LUC emissions globally, due to the multiple mechanisms of leakage. However, these broader import restrictions could drive larger impacts in a few key deforestation-prone export regions, especially Brazil. LUC emissions reductions in these exporting regions could be particularly important, given the large share of LUC emissions in these countries' overall total GHG emissions (Soterroni et al., 2023). LUC emissions reductions could free up emissions in other difficult to abate sectors or those requiring negative emissions technologies, helping these countries achieve their near and longer-term emission reduction goals (Soterroni et al., 2023). Meanwhile, in regions like the USA, which could face increased soybean production and lowered carbon sinks due to broader import restrictions, additional mitigation effort may be needed in other sectors to compensate. As shown in our results, the effectiveness of import restrictions in reducing LUC emissions in key regions relies on a substantial fraction of market share imposing such restrictions. More broadly, the effectiveness of such policies in reducing emissions globally will rely on coordinated action across major oil-crop producing and consuming regions (Bougas et al., 2023) and across sectors.

Our study also highlights the negative economic impacts on exporting regions in the Global South resulting from import restrictions, raising concerns about equity. Declines in production revenue could exacerbate the vulnerabilities that smallholder oil crop producers in these regions already face. Furthermore, our study captures oil palm or soybean producers' full economic responses to switch to other commodities or markets, inherently assuming producers would have access to market information, when in reality, producers (particularly smallholders) often lack awareness about their market options (Lambin et al., 2018). Negative economic impacts in key exporter regions could be worse than shown here and could concentrate on smallholders. Our results validate protectionism concerns voiced by exporters from the Global South, in that oil crop producers in the EU could benefit from import restrictions and receive higher production revenues. Importers like EU or China may face increases in agricultural revenue as a result of import bans, while the U.S. may benefit significantly as a substitute soybean exporter whose supply chains are not linked to deforestation. More broadly, inequitable import restrictions which exacerbate current global inequities between Global North and Global South regions could undermine international relations and hinder climate mitigation progress.

To avoid negative economic impacts faced by exporters in deforestation-prone regions, additional or alternative land use policies and/or financing are needed. Alternative policies, as exemplified by our *Land Protect* scenario could be more effective and economically efficient, while not exacerbating global inequities between countries. This could include REDD+ schemes and agricultural intensification programs. Operationalizing such direct forest protection efforts is challenging, but previous research has highlighted the effectiveness of moratoria (i.e., sector-wide sanctions on the conversion of specific forest lands) alongside improved local governance in reducing deforestation (Lambin et al., 2018).

Given that the stated goal of the EU's regulations is to incentivize producers to reduce land conversion and deforestation, the EU (and regions which follow suit) must take additional actions to help producers implement and certify deforestation-free supply chains. Beyond simply implementing "sticks" in the form of import restrictions, importing regions should also implement "carrots" in the form of additional funding to support oil crop producers (Mark, 2023). EU's deforestation regulations require each producer to certify their specific exports as being deforestation-free before they can be allowed into EU. This will disproportionately present challenges for smallholder producers who lack the financial resources and technical capacity to provide traceability reports to comply with the requirements, and more fundamentally, lack access to high-quality land where they can intensify oil crop production without clearing forests (Mark, 2023). Therefore, additional funding and technical support is needed to help oil crop producers, especially smallholders, build capacity in producing deforestation-free oil crops.

Additional financing for forest conservation, such as the "Tropical Forests Forever" fund announced by Brazil at COP28 could be an important mechanism for ensuring the economic livelihoods of people who live in and protect tropical forests (Paraguassu, 2023). Further cooperation is needed, between exporting regions concerned about negative economic impacts on their producers and importing regions seeking to limit their indirect deforestation impact, to help incentivize forest protection and avoid negative economic impacts for oil crop producers in developing regions. More broadly, Global North regions have announced plans to increase funding, including around $500 million in initial pledges to the loss and damage fund, yet these numbers pale in comparison to estimated damage costs that developing regions could face around $280-580 billion per year (Friedman, 2023). Much more funding is needed to make a dent in addressing the climate change inequities that Global South regions face.

4.5 Limitations and Future work

There are some caveats to our modeling approach. EU's currently enacted deforestation regulations restrict the specific imports (at a supply-chain level) linked to deforestation (EU, 2023). In this analysis, we do not consider the impact of import restrictions on finer-spatial scale regions or targeting specific producers (e.g., companies) whose commodities are linked to deforestation, which has been a key contribution in previous studies (Villoria et al., 2022; Leijten et al., 2023), and which could be considered a more direct interpretation of EU's current policy. Given that our trade flows are modeled at a regional level, we therefore interpret this regulation as a "freeze", holding exports from these deforesting regions constant at 2020 levels, thus preventing future deforestation and land use changes to accommodate increased exports to import-restricting regions.

GCAM accounts for land intensification exogenously over time (i.e., increasing agricultural yields), as well as endogenous land intensification in response to prices (i.e., increase in yield due to higher-cost inputs like irrigation and fertilizer). However, our scenario construction does not assume additional explicit policies focused on intensification of existing oil crop land in deforestation-linked oil crop exporting regions in response to import restrictions, which could allow for increased production without expanding of land footprint. Accounting for such land intensification policies explicitly could reduce market-switching leakage and land-switching leakage and reduce overall deforestation and LUC emissions. Thus, in the absence of such land intensification policies, our scenarios can be considered an upper bound to the level of global emissions leakage possible and a lower bound to how much benefit import restriction policies can provide, in reducing deforestation and LUC emissions.

The capabilities developed for this study could be extended to track bilateral trade of additional commodities, e.g., all seven commodities covered by EU's recent deforestation regulation. Estimated impacts of import restrictions could be larger when accounting for these commodities. Beyond deforestation and LUC emissions, import restrictions could have significant consequences on other planetary boundaries (e.g., local water scarcity). This is an important area for future work. Future work can also compare and quantify the policy costs and benefits of various alternative measures to protecting forest lands globally.

5. Conclusions

5.1 Summary of the dissertation and key policy implications

This dissertation contributes to the literature at the intersection of global trade and climate policy fields. An overarching contribution is in evaluating impacts of agricultural and energy trade and trade policies across multiple, integrated sectors. Together, the three essays highlight the potential roles of specific types of resource trade in the future, as the world undertakes climate mitigating actions. I analyze global and regional implications resulting from changing trade dynamics, including specific opportunities and vulnerabilities that exporters or importers could face with regard to economic welfare, sectoral mitigation burden, food or energy security, underutilized infrastructure assets, and land and water use.

In Essay 1, I showed that there is a significant economic opportunity for several LAC regions (particularly, Argentina, Brazil, Uruguay, and southern S. America) in increasing market share. Total net export revenue across LAC could reach \$110-\$270 billion annually by 2050. Such production and exports will be critical to meeting agricultural demands globally. However, unsustainable or inequitable outcomes and trade-offs need to be planned for. Agricultural production and emissions reduction goals could have trade-offs with one another. Increased consumer agricultural expenditures, resulting either from market integration, climate mitigation policies, or both combined could pose risks of food insecurity for low-income groups. Market integration might help mitigate severe increases in consumer expenditure that result from climate mitigation measures in some regions, but additional policy mechanisms, to redistribute gains more equitably may be needed in others (e.g., in Mexico, Brazil, and Argentina). Major land use changes and accompanying water withdrawals could result in water scarcity concerns in specific basins. For example, Rio Colorado in Argentina, and Rio Lerma and Rio Grande in Mexico could approach moderate water scarcity by 2050 and benefit specifically from more targeted investments in water infrastructure.

In Essay 2, I showed that new global investments in LNG and pipeline export infrastructure could respectively range from 330-1330 and 130-440 million tons per annum (MTPA) by 2050, the lower end of these ranges achieved through faster transitions to low-carbon energy systems along with limited trade. For importing regions there are several potential strategies in improving energy security. Advances in LNG technology could allow regions to import natural gas more flexibly from a wider set of regions, however, this requires significant investment in new LNG trade infrastructure. Importing regions could shift to increase reliance on domestic sources, including other fossil and renewable resources. Alternatively, faster transitions to a low-carbon energy system or broader restructuring of the economy could facilitate less demand for natural gas. In this way, climate policies can hold synergies for improving energy security. Meanwhile for exporting regions, their future risks depend on which markets they produce gas for. Regions which produce gas largely for exports, and export largely through pipelines (e.g., Russia) could face larger declines in production (and higher underutilization), under the factors explored in this study.

In Essay 3, I showed that currently enacted import restrictions in the EU have minimal impact on reducing deforestation and LUC emissions due to the EU's otherwise small and diminishing share of global palm and soy demand. However, if extended beyond the EU, import restrictions could drive larger reductions in LUC emissions in key oil crop exporting regions by 2050— up to 0.9% in Indonesia, 1.5% in the rest of Southeast Asia, 3.8% in Argentina, and 6.7% in Brazil, relative to a scenario with no import restrictions. Given the large share of LUC emissions in these countries' total budgets, this could free up emissions in difficult-to-abate sectors. However, globally, emissions leakage could prevent import restrictions from reducing LUC emissions globally and coordinated action is needed across regions and sectors to compensate for such leakage. Meanwhile, key exporting regions could face losses in cumulative agricultural production revenue ranging $4.1-$6.1 billion by 2050, as a result of import restrictions. This raises concerns about equity impacts on Global South exporting regions and could undermine multilateral climate mitigation progress. Therefore, additional or alternative land use policies and financing should be considered.

5.2 Methodological contributions

A main methodological contribution, across essays, is improved representations of global trade, appropriate for different commodities and contexts, within a leading IAM, GCAM. Essay 1 represented increased market integration over time, over all agricultural (crop and livestock commodities), within the Armington global pool trade structure. Increased market integration parameters were previously only included on crop commodities (Zhao et al., 2021). Essay 2 introduced the Armington regional pool trade structure within GCAM for representing commodities (e.g., pipelines) whose trade is constrained to a particular regional area. Essay 3 introduced the bilateral trade structure within GCAM, allowing for the explicit tracking of the source and destination for traded commodities. The bilateral trade structure in GCAM allows for more realistic representation of trade dynamics in the near term.

Some additional methodological contributions are summarized as follows. Essay 1 contributed a format to synthesize together and evaluate multi-dimensional economic and environmental impacts experienced by different groups (e.g., producers and consumers) at a sub-regional (water-economy region level). This format allows an easier comparison of impacts across different sub-regions, as well as across multiple scenario drivers. This format also involved a new method of downscaling livestock revenues and emissions to the sub-regional level, to be able to see producer revenues and AFOLU emissions at the sub-regional level.

From Essay 2, a key contribution is the new representation of two separate trade infrastructure pathways (pipeline and LNG trade) within a well-established IAM, GCAM. The new trade structures allow us to add on different types of costs (e.g., liquefaction, shipping, regasification, or pipeline costs) for trade infrastructure in different regions. The vintaged structure employed here allows us to quantify new infrastructure additions and underutilization, which has previously only been quantified in power sector literature.

5.3 Policy contributions

Essay 1's analysis of trade-offs between different policy goals (e.g., between economic development and climate mitigation goals), and across scales (e.g., between river basin- and national-level) could help facilitate integrated policy making between sectors across scales.

Essay 2 has already opened the door to timely and policy-relevant contributions in different regional settings, including importing and exporting regions. Based on the capabilities developed in Essay 2, I contributed to a policy relevant analysis for the EU gas crisis, exploring possible strategies for Europe in replacing Russian gas (Nikas et al., 2024). Relevant to President Biden's recent announcement pausing and evaluating levels of LNG exports (The White House, 2024), I am contributing to policy analysis of the global impacts of increased US LNG supplies.

Essay 3's quantifications of import restrictions' impacts on reducing deforestation and LUC emissions, and their broader economic implications, are a timely input to global discussions surrounding EU's recent deforestation regulations, and more broadly, on the role of import-side trade policies in achieving climate mitigation goals. This analysis could also help countries in determining sectoral contributions to NDCs and inform other importing regions considering import restrictions.

5.4 Caveats

Each essay in this dissertation has its own individual caveats related to the modeling assumptions used and the level of detail in the analysis. Here, I summarize some of the broad types of caveats across all three essays, and for integrated assessment modeling (IAM) research in general.

5.4.1 Resolution of detail and interactions modeled

The strength of global IAMs, like GCAM, lies is in focusing on the *interactions between* regions and sectors rather than modeling all the detailed sectoral or regional processes. Outputs from GCAM analysis, including those from the essays in this dissertation, can provide boundary conditions to finer scale (sectoral or regional models). Many detailed processes reflective of actual trade conditions are not modeled. International trade occurs only between the 32 (or 33) regions in GCAM. Within-region trade, which could account for significant volumes of trade, is not considered. Finer scale processes (e.g., at gridded spatial scales) are not considered. Commodities traded are aggregated (e.g., soybean includes the trade of soybeans, soybean oil, and soybean cake). End-uses for each commodity in various sectors do not differentiate between domestic versus imported commodities. Regionally specified trade costs, (e.g., costs varying by distance across which commodities are traded) are not included. Production and consumption within a region are considered in the aggregate, e.g., multiple consumers with different characteristics, like income levels, are not considered.

Similarly, across essays, scenario constructions are stylistic and broad. Scenario factors such as economy-wide climate policies and global market integration or limitation (i.e., the lowering or increasing of trade barriers between regions) are modeled globally without accounting for specific climate regional climate policies, trade agreements or geopolitical shifts. In Essay 3, the import restrictions considered do account for specific regional details (i.e., specific import restricting regions and deforesting export regions). However, in reality, import restrictions will not be imposed across entire countries but rather on specific supply chains within countries, which are not captured in this modeling.

Many dimensions of uncertainty could affect the future projections of trade and its implications as explored in this dissertation. The scenario factors explored in each essay of this dissertation are new and represent not-well-understood dynamics of future trade. Across essays, the key takeaways are not the exact magnitudes or percent changes projected in each scenario, but rather the broad trends and insights that arise from scenario comparison. Many of the metrics presented thus focus on relative changes *between* scenarios, rather than absolute values, to focus discussion on how the specific scenario factors affect results. Thus, accounting for the many factors that could affect the specific magnitudes is not a focus of this work. A broader uncertainty quantification (i.e., sensitivity analysis) in understanding how the projections shown here would change, as a result of the scenario factors explored here in combination with other uncertainties has not yet been undertaken but is an important area for further work.

Indeed, many additional uncertain factors, beyond those chosen and explored in each essay could also affect future projections of trade and its implications. These could involve uncertainties that affect supplies (e.g., the relative substitutability of different energy supply technologies or agricultural commodities) or demands (e.g., broader socioeconomic uncertainties, competition from technologies demanding various fuels). Two key dimensions of uncertainty, climate change impacts and stringency of climate mitigation ambition are discussed in further detail below (sections 5.4.3 and 5.4.4, respectively).

A key caveat is that all three essays rely on the inherent structural uncertainty embedded in a single IAM, GCAM. Using a single IAM to conduct scenario analysis is reasonable because differences that arise between scenarios can be ascribed to the scenario factors themselves, rather than the structural uncertainty embedded in the model. While using other models to represent similar scenarios could certainly affect the magnitudes and some of the insights drawn here, it is hard to make a systematic comparison of how insights could be different if different models are used. As argued in Zhao et al. (2024), differences between models arise due to different structure, data sources, and parameters used, making it difficult to draw meaningful statistical inferences from results across models. More technical comparisons of models, aimed at systematically addressing differences in structure, data, and parameters could be useful, but this goes beyond the scope of most existing community multi-modeling comparison projects. Such work can be considered frontier work for the IAM community.

5.4.3 Climate change impacts

Importantly, climate impacts on agriculture, water, or energy systems have not been accounted for in any of the essays. Given that Earth has already warmed an average of 1.1°C (IPCC, 2023), climate change impacts on our agricultural and energy systems are likely inevitable as a baseline condition. Climate change impacts affecting agricultural production conditions (e.g., runoff availability, agricultural productivity) could change the dynamics of agricultural trade across regions globally. Climate change could also affect energy systems, e.g., via the availability of biomass supply across regions, or more directly, by affecting energy demands (e.g., heating and cooling demands of buildings, cooling demands of thermal energy generation or industrial systems). Vulnerability to climate change impacts could also exacerbate the vulnerabilities that certain groups face (i.e., the distributional consequences) as a result of changing trade dynamics.

5.4.4 Stringency of climate mitigation ambition

In each essay, at least one climate mitigation pathway is modeled, and the results explore how agricultural or energy commodity trade could be affected in a world pursuing climate mitigation policy. However, the degree or stringency of climate mitigation ambitions (taken by each country individually, and the world as a whole) represent a key area of uncertainty which could affect the results shown in these essays. Moreover, policy choices about which ambitious actions to take (i.e., in which sectors, or through which policy instruments) represent even more degrees of uncertainty in representing future climate mitigation ambitions.

In Essay 1, highly ambitious policies are represented in the agriculture and land use sectors through carbon pricing on the land sector (on both CO2 and non-CO2 GHG emissions), as well as more steep marginal abatement cost (MAC) curve reductions in livestock emissions, representing technological advancements (see Section 2.2.2 for details). These policies are much more ambitious than what has been proposed in Latin American regions in the agricultural and land use sector. The resulting land use changes represent a steep departure from historical trends (i.e., afforestation instead of deforestation). Such a stringent climate mitigation pathway represents an extreme case and allows us to compare against the low-extreme (no-climate policy case); less stringent climate mitigation policies would likely yield results that fall in between these two extremes. The high ambition scenario highlights several trade-offs, such as high consumer prices and expenditures, and loss of livestock production in some regions. Rather than stringent ambition across the entire land sector, future work could explore stringency in particular levers of land-based mitigation policy in Latin America, e.g., between high levels of afforestation, BECCS usage, or non-CO2 GHG mitigation. Such work has been explored in previous studies globally (e.g., Zhao et al., 2024; Merfort et al., 2023), but the implications for key agricultural producing regions, like Latin America, have not been explored. Essay 2's focus on natural gas provides a very interesting example of a commodity whose potential to help achieve climate mitigation goals depends significantly on the climate trajectory that the world is set to achieve. Because of natural gas's middle position between lower- or zero-emitting technologies (e.g., renewables and nuclear) and higher emitting technologies (e.g., coal), whether natural gas can help or hinder the achievement of climate mitigation targets depends on what fuels it substitutes for, which depends on what temperature target the world is on track to achieve. A previous study by Yang et al. (2022) showed that— across 1.5°C, 2°C and 3°C temperature targets— substitution from coal to LNG-derived gas in the power sector could reduce global CO2 emissions, but in the long term, planned LNG expansion is not compatible with 1.5 and 2°C targets. However, in a 3°C scenario, LNG could be an attractive option to reduce emissions and thus expanding LNG infrastructure could be considered as "insurance" against lack of climate ambition to achieve 1.5-2°C (Yang et al., 2022). Further complicating this picture is the availability interacting technologies (see section 2.5), such as carbon dioxide removal (CDR) technologies, which could make natural gas a more viable fuel in the long term. In Essay 2, we define a 1.5-2°C compliant energy transition pathway globally with considerable CDR availability and find that LNG grows through the coming decades. However, this outcome and its magnitude could change depending on levels of climate mitigation ambition assumed (in different regions and globally) as well as technology availability. An interesting topic for future work would be to define multiple climate mitigation ambition pathways (as was done in Yang et al., 2022), but look at natural gas usage across the full energy system (e.g., power, industry, buildings sectors) and the availability of interacting technologies to understand LNG's role in future energy systems.

Essay 3 takes a realistic approach in representing climate mitigation ambitions for each region, in line with countries' NDC targets through 2030 followed by ratcheting ambition (Iyer et al., 2022). In doing so, we implicitly assume a pathway for the level of first- versus second-generation bioenergy growth in the coming decades (see Appendix C.2 for discussion on the implications of this). The bioenergy pathway assumed in the baseline has important implications for the results of this study. If growth of second-generation biofuels is higher than projected (e.g., due to more stringent climate mitigation action), there would be lower levels of first-generation biofuels in the *REF* scenario, and consequently, smaller magnitudes of change (in oil crop trade flows) and lower effectiveness of import restrictions in reducing deforestation and LUC emissions. Nevertheless, because oil crops are demanded not only for bioenergy, but for food, non-food, and animal feed demand, import restrictions will still likely play a role (albeit minimal) in reducing global deforestation and LUC emissions across a wide range of uncertain climate mitigation ambition pathways.

5.5 Areas for further research

5.5.1 Further development of bilateral trade capabilities within an IAM framework

Recent climate and trade policy opens avenues for further research involving bilateral trade. Countries have been deploying import-side measures (e.g., deforestation regulations or carbon border-adjustment mechanisms) as climate-oriented policies. Countries have also been deploying export-side measures, for example, Indonesia's ban on critical mineral exports (Maulia, 2023), aimed at fostering domestic industries. Such export measures will also have significant implications for broader energy system transitions and the achievement of climate mitigation goals globally. Additional sectoral climate policies, which impact commodities that are significantly traded (i.e., emissions-intensive, trade exposed (EITE) commodities) will also be important in understanding future implications in a climate-mitigating world.

As an example, one recent export-related decision, the Biden Administration's recent pause and evaluation of U.S. LNG exports (The White House, 2024) and one sectoral climate policy, the EPA's recent regulations on methane emissions from oil and gas production in the US (US EPA, 2023) combine to provoke important research questions. First, if more US LNG is exported to the rest of the world, what fuels will it displace (e.g., coal, renewables, or other natural gas), and in which regions (e.g., Asia or Europe, which could have very different demand trajectories)? Second, how will GHG emissions, across the entire supply chain (production, liquefaction, shipping, and consumption) compare across different exporters?

To be able to answer such questions fully, I believe an important area for future research is in further developing bilateral trade capabilities within an integrated assessment model like GCAM. This would allow for the tracking of differentiated emissions intensity of commodity production across different producing regions and would allow us to understand specific substitution effects in different regions. Water or land intensities (i.e., virtual water and virtual land trade) of commodities could also be better tracked. This could also allow us to reflect differentiated trade costs associated with different bilateral trade routes. Broadly, a global bilateral trade framework could be developed for multiple commodities and sectors. Some examples could include representing bilateral trade of specific LNG contracts, all of the agricultural commodities included in EU's deforestation regulation, and critical mineral supply chains.

Furthermore, additional model developments could reflect the fact that representing specific bilateral trade relationships adds realistic detail in the near term but may not hold in the long term. Further work can develop model capabilities to allow for increasing market integration and broader uncertainty in the long-term.

5.5.2 Broader engagement with other research methodologies and focus areas

Beyond IAM research, work in this dissertation sets the stage for broader engagement with complementary methodologies. In exploring the opportunities and vulnerabilities that could concentrate on particular importing or exporting regions, future work could use econometrics and social science methodologies to explore a broader range of well-being and equity implications that could result from the changing dynamics of global agricultural or energy resource trade in a climate-mitigating world. Future work can also address trade's role in other aspects of climate policy, including resilience and adaptation.

Complementary methodologies could be used to evaluate a broader range of metrics that more directly address issues of well-being and equity. For example, beyond first-order economic impacts (i.e., aggregated measures of producer revenues, consumer expenditures, stranded assets), future work looking at impacts of trade and climate policies could look at distributional impacts across income or racial/ethnic groups, or by gender and age. Other metrics, such as consumer and producer surplus, and other dimensions of food, energy, and water security (e.g., accessibility, affordability, reliability, and quality) could also be evaluated. Engaging with other methodologies could also facilitate improved comparison of the policy costs, benefits and efficiency or effectiveness across different climate mitigation strategies. For example, in comparing the costs of direct land protection policies with indirect policies (i.e., import restrictions) aiming to protect forests and limit deforestation and LUC emissions, bottom-up approaches to policy evaluation could be taken to quantify the costs of various supply-chain interventions (Lambin et al., 2018).

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Appendix A: Supplementary material for Essay 1

A.1 Global Change Analysis Model (GCAM) details

Aggregate categories	Crop staples	Crop non-staples	Fodder crops[i]	Livestock	Biomass
Agricultural commodity categories in GCAM	Corn, OtherGrain, Rice, RootTuber, Wheat	OilCrop, FiberCrop, PalmFruit, SugarCrop, MiscCrop[ii]	FodderGrass, FodderCrop	Beef, Dairy, Pork, Poultry, SheepGoat	BiomassGrass, BiomassTree

[i]Fodder crops are not included in agricultural production and net trade revenues (as they are not traded), but are included in crop land

[ii]MiscCrop includes several commodities including nuts, seeds, fruits, vegetables, and legumes.

Table A-1. GCAM's agricultural (crop and livestock) commodities as represented in aggregate categories in this study's figures.

A.2 Scenario details

		Global market integration	
		Fixed (historical) preferences between domestic vs. international commodities	*Global integration of markets (preference bias erosion) over time*
Climate mitigation policy	*No policy*	Reference (REF)	Market integration (MI)
	CO2 policy	*CO2 mitigation policy (CO2)*	*Market integration + CO2 mitigation policy (MI + CO2)*
	GHG policy (includes mitigation of CO2 and Non-CO2 emissions), USA livestock MAC curves across regions	Climate mitigation policy (CM)	Market integration + Climate mitigation policy (MI + CM)
	GHG policy with differentiated livestock MAC curves across regions	*Climate mitigation policy with differentiated MAC curves (CM (diff. MAC))*	*Market integration + Climate mitigation policy with differentiated MAC curves (MI + CM (diff. MAC))*

Table A-2. Full scenario design (including sensitivity scenarios).

A.2.1 Additional details on market integration dimension (MI)

Text A.2.1. High bias erosion scenario (MI): Zhao et al. (2021) estimated trade integration rates for four 5-year periods historically (1995-2015) with confidence intervals for each time period based on varying trade preference parameters. The high bias erosion scenario uses the parameters associated with the highest upper value of the 95% confidence interval range of rates of trade integration, observed across historical time periods and parameter specifications. This scenario represents the close to the highest rate of trade integration observed historically and can thus be considered an upper bound to the potential future rate of global market integration. The parameters used in this scenario imply a rate of market integration of 1.23 per 5-year interval, indicating a half-year of ~17 years. In other words, it would take 17 years to achieve half the global agricultural market integration effect of full home preference bias erosion (Zhao et al., 2021). It is also important to note that regional demand and trade are also responsive to prices and expand with socioeconomic drivers. However, without an explicit integration trend, the Armington structure would likely not capture faster trade growth than GDP or consumption, i.e., the missing globalization issue. Thus, as opposed to an unrealistic no-trade counterfactual scenario, our reference scenario represents a reasonable future of limited further global market integration due to lower non-market barriers.

A.2.2 Additional details on climate mitigation dimension (CM)

Text A.2.2. Climate mitigation dimension components:

1. Linear constraint to achieve 90% reduction in CO2 emissions (FFI + LUC) in each of the 8 LAC regions and rest-of-world (ROW) as a whole by 2050.
2. Price LUC CO2 emissions at 10% the level applied on FFI CO2.
3. Apply corresponding ROW CO2 price to all non-CO2 GHG emissions in all 8 LAC regions and ROW as an explicit tax.
4. MAC curves for non-CO2 GHG emissions based on assumed marginal abatement cost (MAC) curves for each region and technology, representing the level of emissions that can be reduced per cost value, based on the non-CO2 GHG price.
    a. In the CM scenario, we apply the USA livestock MAC curves to all regions.
    b. In the CM (diff. MAC) scenario, each region uses its GCAM default, regionally differentiated livestock MAC curve.
5. Constraint of 100 EJ on first- and second-generation biomass, consistent with deployment levels assumed in AR5 WGIII report (IPCC, 2014). We also lowered growth rates of second-generation biomass globally, consistent with Zhao et al. (2022).

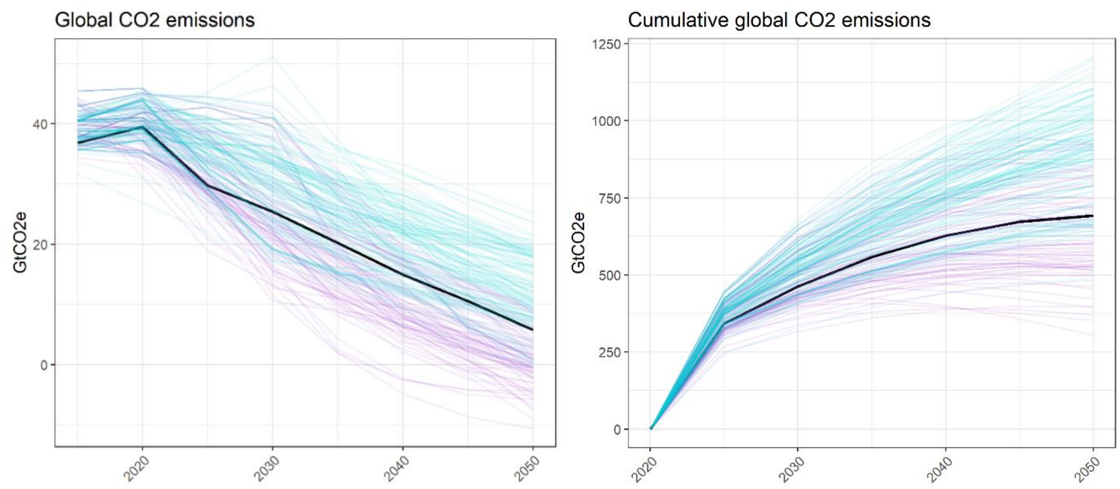


Figure A-1. a) Global CO2 and b) Cumulative global CO2 emissions compared to IAMC Scenario Database (Huppmann et al., 2019). Blue lines represent 2C scenarios, purple lines represent 1.5C scenarios. Our CM scenario is shown as the thick black line. These figures indicate that our CM scenario represents a "well below 2C" scenario. Our CM scenario pathway results in less than 700 GtCO2 of cumulative global CO2 emissions by 2050, which is associated with a 67% chance of staying below 1.7C (IPCC, 2022)

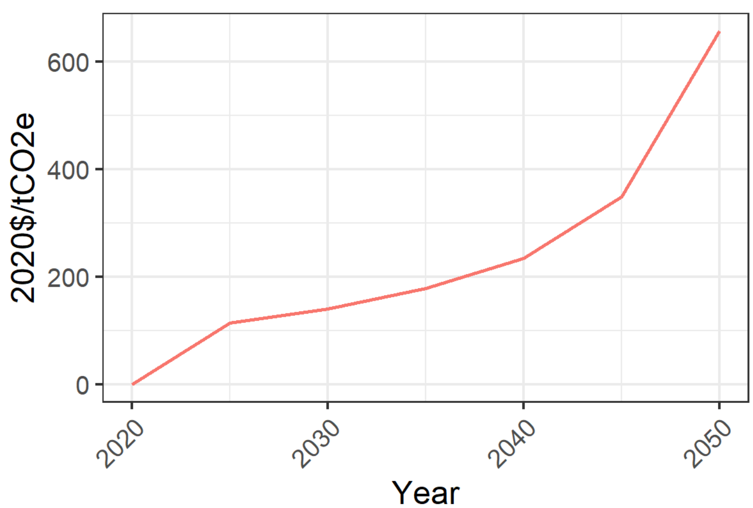


Figure A-2. Non-CO2 GHG price applied to all regions under CM scenarios. Non-CO2 GHG price is applied as an explicit tax on Non-CO2 GHG emissions.

A.3 Economic and environmental metrics

		LAC and ROW	**LAC economies**	**LAC WERs (% change relative to REF)**
Economic outcomes	**Producers:** Agricultural production revenue ($2020)	X	X	X
	Producers: Agricultural net trade revenue ($2020)	X	X	
	Consumer agricultural expenditures per capita ($2020/p)		X	X
Environmental outcomes	**Climate:** GHG emissions (MtCO2e)	X		
	Land: Crop land fraction			X
	Land: Pastureland fraction			X
	Water: Water withdrawals (m^3)			X

Table A-3. Economic and environmental outcomes considered in this study, and the resolution at which they are presented in the main paper.

A.3.1 Agricultural production, consumption, and trade equations

1. $Agricultural\ production\ revenue\ = Export\ production\ revenue\ [\$] + Domestic\ production\ revenue[\$] = \sum_{commodities} production\ volume\ [Mt] * producer\ price\ \left[\frac{\$}{Mt}\right]$

2. $Net\ trade\ revenue\ = Export\ production\ revenue\ [\$] - Import\ value[\$] = \sum_{commodities} Export\ volume\ [Mt] * producer\ (export)\ price\ \left[\frac{\$}{Mt}\right] - Import\ volume\ [Mt] * import\ price\ \left[\frac{\$}{Mt}\right]$

3. $Consumer\ agricultural\ expenditure\ per\ capita = \frac{Domestic\ value\ [\$] + Import\ value[\$]}{Population\ [p]} = \frac{\sum_{crops} Domestic\ production\ volume\ [Mt] * domestic\ price\ \left[\frac{\$}{Mt}\right] + Import\ volume\ [Mt] * import\ price\ \left[\frac{\$}{Mt}\right]}{Population\ [p]}$

   Note: GCAM does not capture costs along the supply chain from agricultural producer to consumer (e.g., labor, processing, transport, taxes) and other value-added increases. Therefore, we focus in the Results section on % changes in consumer expenditure per capita across scenarios, which are driven by changes in domestic vs. import production and prices.

A.3.2 Livestock downscaling

Text A.3.2. While crop commodities are produced at the water-economy region (WER) scale, livestock commodities are produced at the economy-region scale. To show total agricultural production revenues (including both crop and livestock commodities) at the WER-scale, we downscaled livestock production using Tethys gridded basin animal data and basin/region livestock water withdrawal data. Processing scripts for this downscaling are included in the meta-repository at https://github.com/brinday/yarlagadda-etal_2022_EarthsFuture.

A.3.3 Crop harvested area adjustment

Text A.3.3. GCAM reports output of crop land. To convert to harvested area (accounting for multi-cropping), we multiplied each crop production volume by its number of harvests per year, which is differentiated by basin, crop type, irrigated or rainfed, low or high agricultural yield, and year.

A.4 Additional results (figures and tables)

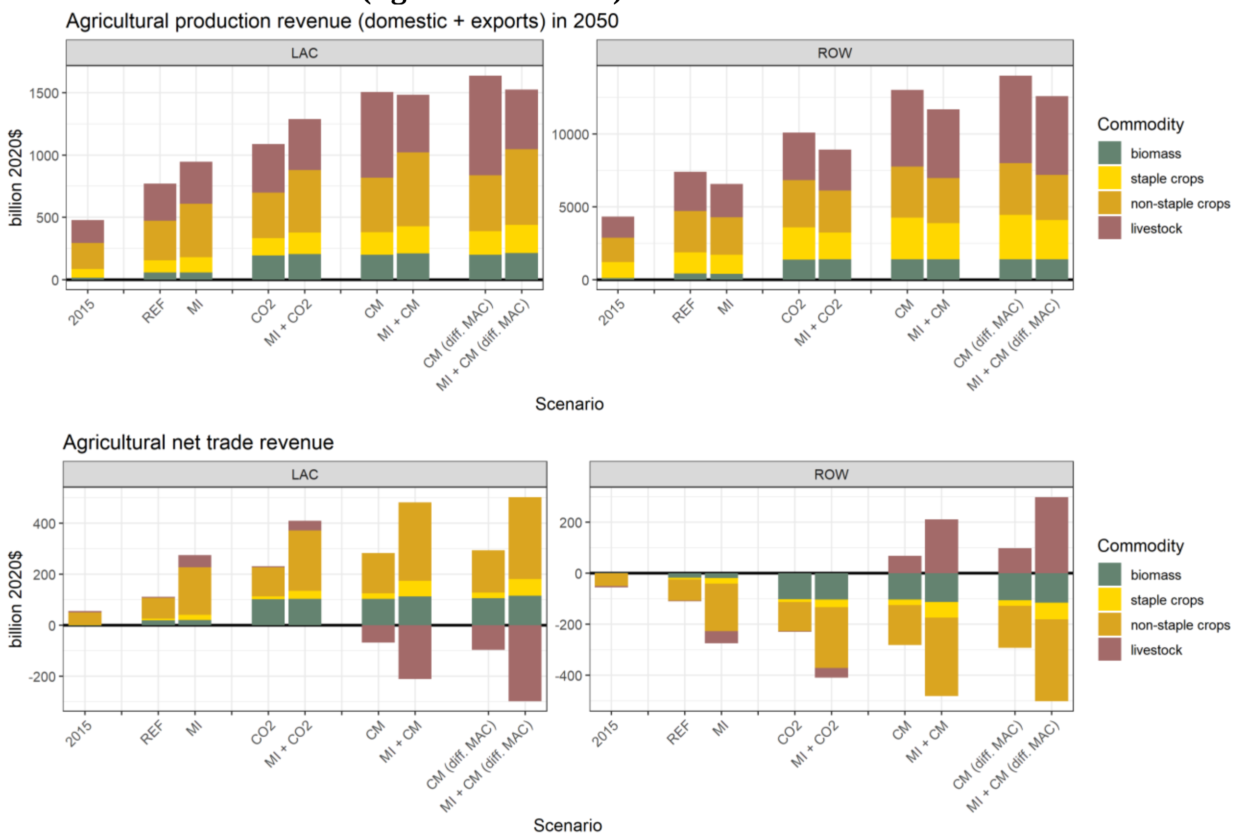


Figure A-3. a) Agricultural production revenue and b) Agricultural net trade revenue in LAC and rest-of-world (ROW) aggregated regions, across all scenarios (including sensitivity scenarios). 2015 = 2015 historical data. All other bars represent 2050 projections. Scenarios: REF = Reference, MI = Faster market integration on crops and livestock, CO2 = climate mitigation policy on CO2 (FFI and LUC), CM = climate mitigation policy on CO2 and non-CO2 GHGs. Diff. MAC indicates sensitivity scenarios in which livestock MAC curves are regionally differentiated.

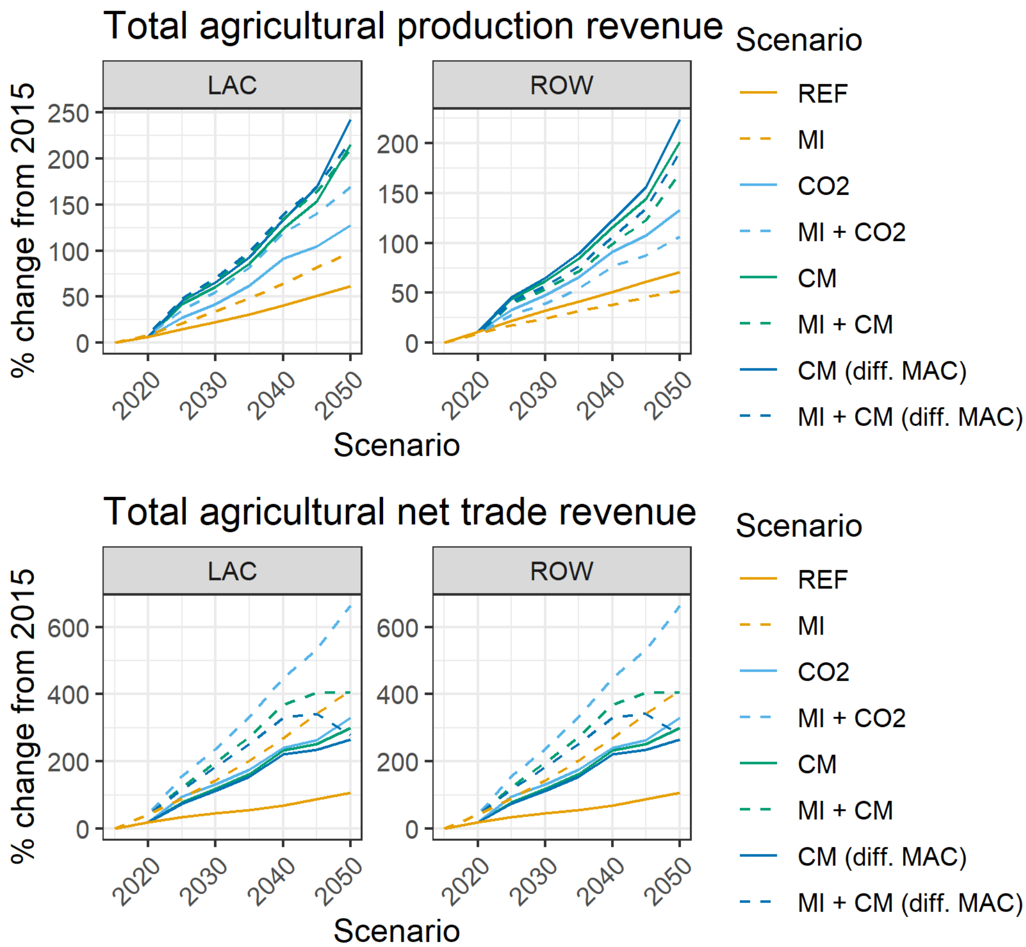


Figure A-4. % change relative to 2015 for a) Total agricultural production revenue and b) Total agricultural net trade revenue in LAC and rest-of-world (ROW) aggregated regions, across all scenarios (including sensitivity scenarios). Scenarios: REF = Reference, MI = Faster market integration on crops and livestock, CO2 = climate mitigation policy on CO2 (FFI and LUC), CM = climate mitigation policy on CO2 and non-CO2 GHGs. Diff. MAC indicates sensitivity scenarios in which livestock MAC curves are regionally differentiated.

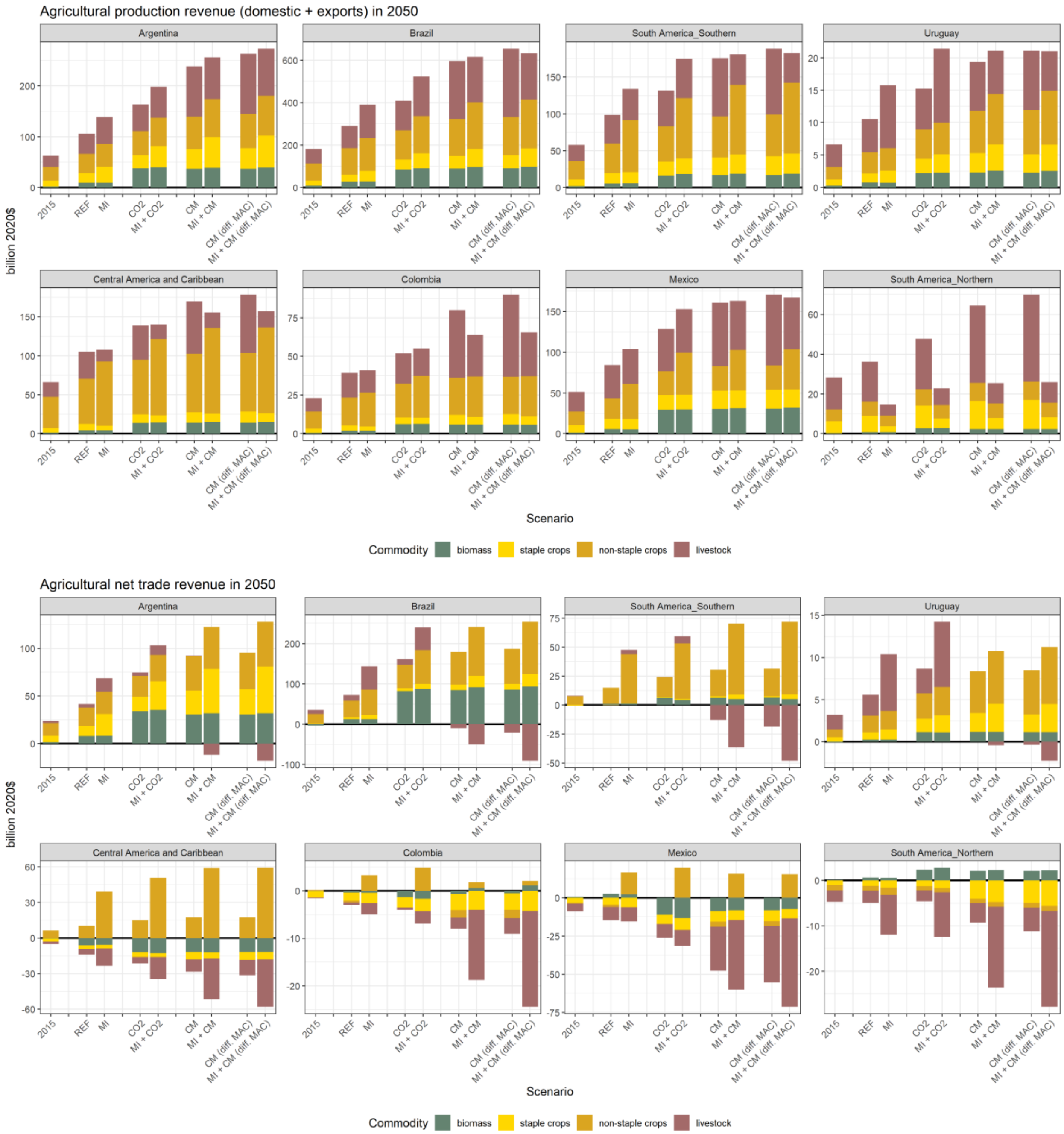


Figure A-5. a) Agricultural production revenue and b) Agricultural net trade revenue across the 8 LAC regions, across all scenarios (including sensitivity scenarios). 2015 = 2015 historical data. All other bars represent 2050 projections. Scenarios: REF = Reference, MI = Faster market integration on crops and livestock, CO2 = climate mitigation policy on CO2 (FFI and LUC), CM = climate mitigation policy on CO2 and non-CO2 GHGs. Diff. MAC indicates sensitivity scenarios in which livestock MAC curves are regionally differentiated.

Figure A-6. a) Livestock production revenue and b) Livestock net trade revenue across all GCAM regions. 2015 = 2015 historical data. All other bars represent 2050 projections. Scenarios: REF = Reference, MI = Faster market integration on crops and livestock, CO2 = climate mitigation policy on CO2 (FFI and LUC), CM = climate mitigation policy on CO2 and non-CO2 GHGs.

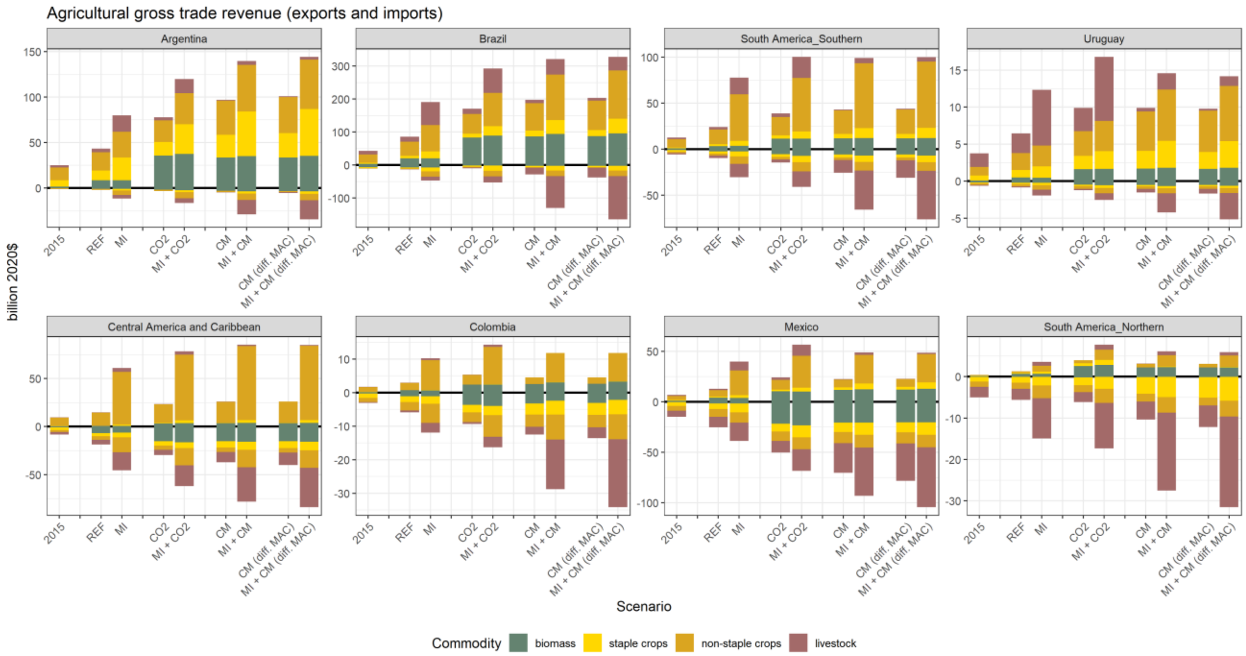


Figure A-7. Agricultural gross trade (exports and imports) revenue across the 8 LAC regions, across all scenarios (including sensitivity scenarios). 2015 = 2015 historical data. All other bars represent 2050 projections. Scenarios: REF = Reference, MI = Faster market integration on crops and livestock, CO2 = climate mitigation policy on CO2 (FFI and LUC), CM = climate mitigation policy on CO2 and non-CO2 GHGs. Diff. MAC indicates sensitivity scenarios in which livestock MAC curves are regionally differentiated.

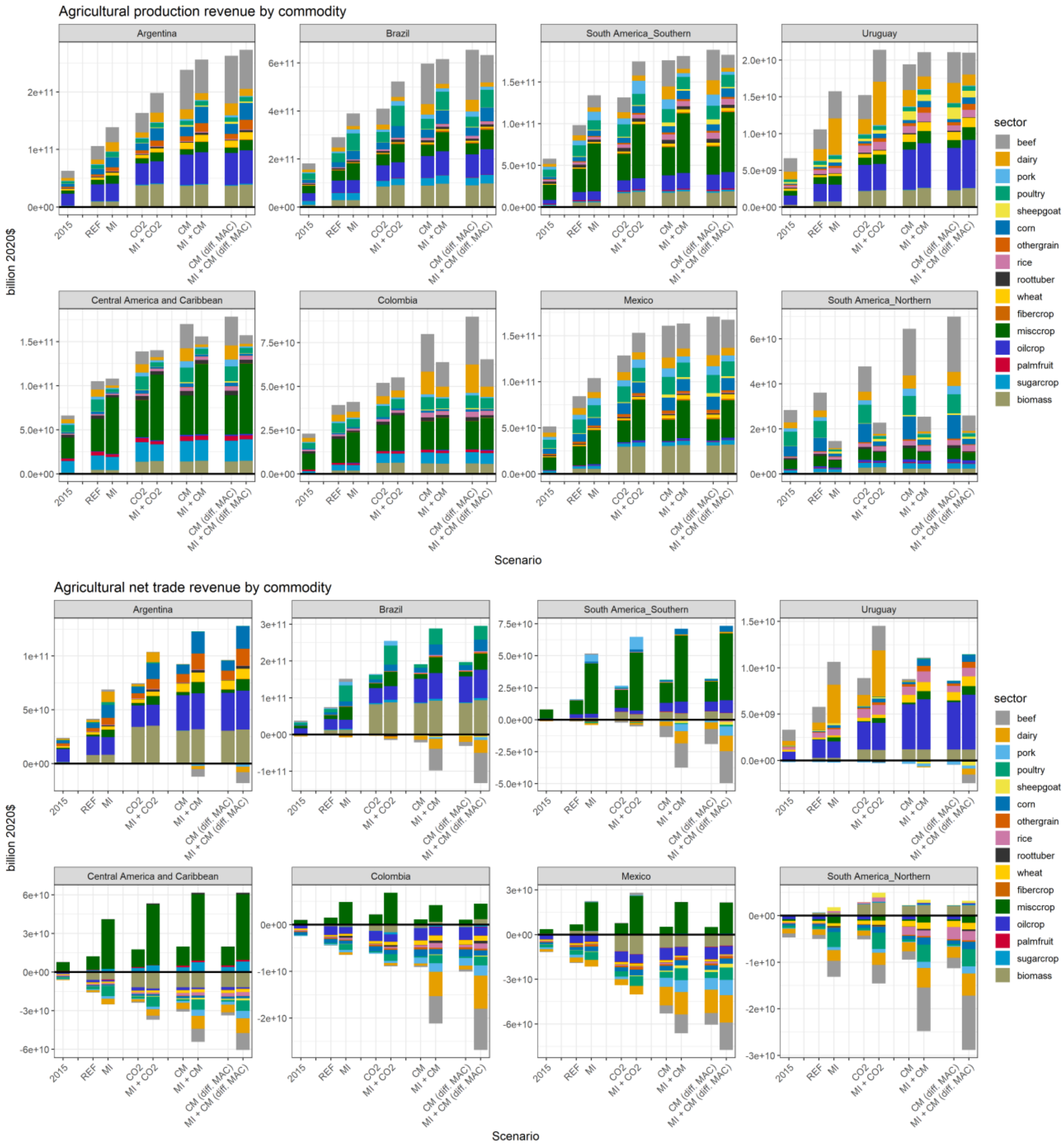


Figure A-8. a) Agricultural production revenue and b) Agricultural net trade revenue by commodity across the 8 LAC regions, across all scenarios (including sensitivity scenarios). 2015 = 2015 historical data. All other bars represent 2050 projections. Scenarios: REF = Reference, MI = Faster market integration on crops and livestock, CO2 = climate mitigation policy on CO2 (FFI and LUC), CM = climate mitigation policy on CO2 and non-CO2 GHGs. Diff. MAC indicates sensitivity scenarios in which livestock MAC curves are regionally differentiated.

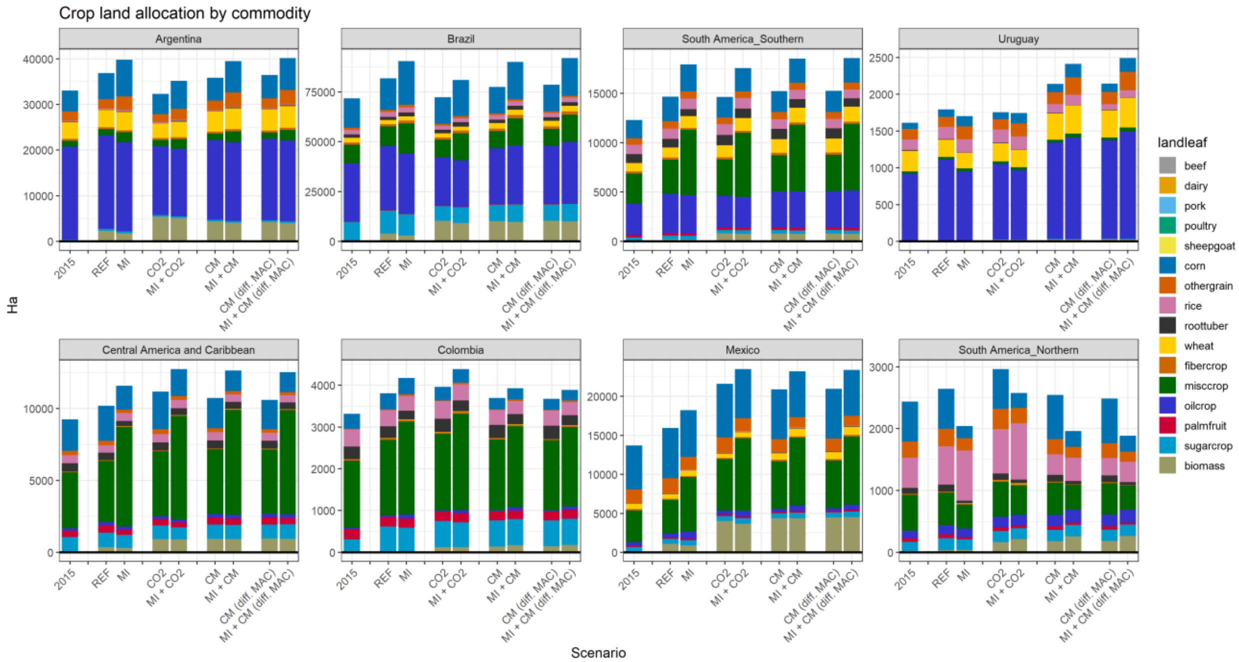


Figure A-9. Crop land allocation by commodity across the 8 LAC regions, across all scenarios (including sensitivity scenarios). 2015 = 2015 historical data. All other bars represent 2050 projections. Scenarios: REF = Reference, MI = Faster market integration on crops and livestock, CO2 = climate mitigation policy on CO2 (FFI and LUC), CM = climate mitigation policy on CO2 and non-CO2 GHGs. Diff. MAC indicates sensitivity scenarios in which livestock MAC curves are regionally differentiated.

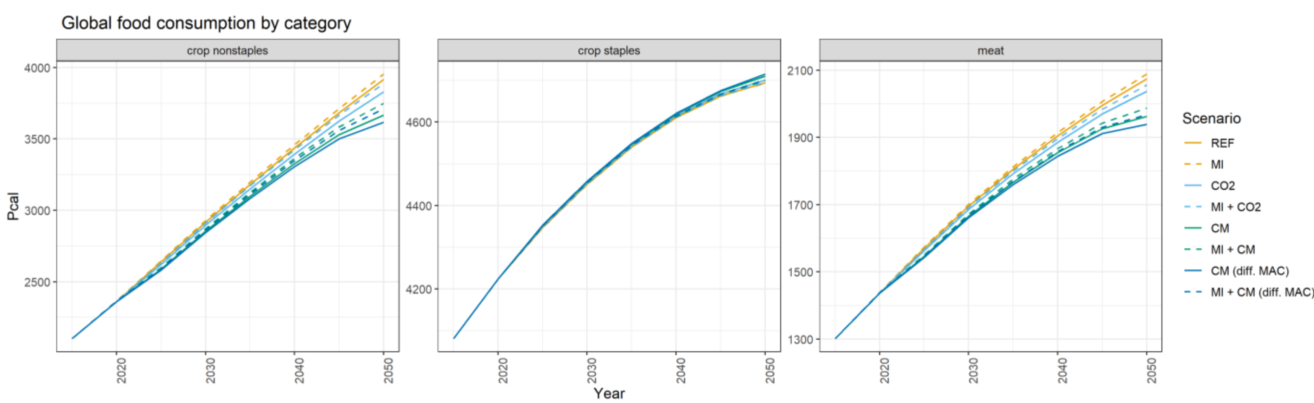


Figure A-10. Global food consumption by category (crop non-staples, crop-staples, and meat). Under the CM scenario, there is a 5% reduction in meat consumption relative to REF globally.

		REF	MI	CO2	MI + CO2	CM	MI + CM	CM (diff. MAC)	MI + CM (diff. MAC)
Argentina	beef	34	45	102	109	342	334	446	435
Brazil	beef	38	51	138	139	592	562	791	756
SAS	beef	31	36	94	93	371	335	494	452
Uruguay	beef	30	59	87	121	349	345	485	470
CAC	beef	51	32	144	97	382	297	480	387
Colombia	beef	46	43	103	100	525	483	714	666
Mexico	beef	26	33	67	78	303	291	408	394
SAN	beef	16	-5	53	21	218	168	291	238
Argentina	corn	17	43	80	119	111	154	115	159
Brazil	corn	1	24	48	79	79	103	83	106
SAS	corn	5	15	47	67	72	87	76	91
Uruguay	corn	7	39	47	92	72	108	76	111
CAC	corn	-8	-15	16	3	68	53	78	64
Colombia	corn	-5	-3	24	27	97	88	107	95
Mexico	corn	8	12	41	48	87	85	92	89
SAN	corn	-14	-38	8	-26	20	-14	22	-12

Table A-4. 2050 % change in beef and corn prices relative to 2015 in all LAC economies, across all scenarios.

		REF	MI	CO2	MI + CO2	GHG	MI + GHG	GHG (diff. MAC)	MI + GHG (diff. MAC)
Argentina	beef	43	46	37	33	25	8	23	3
Brazil	beef	22	37	9	6	-4	-39	-8	-48
SAS	beef	56	72	50	45	9	-42	1	-54
Uruguay	beef	13	26	-5	8	-58	-60	-61	-71
CAC	beef	46	31	37	-10	30	-48	28	-55
Colombia	beef	52	54	51	49	38	-4	35	-18
Mexico	beef	54	73	64	79	30	5	24	-7
SAN	beef	25	-38	33	-24	19	-55	15	-63
Argentina	corn	58	130	33	89	51	113	54	117
Brazil	corn	47	111	44	99	40	104	41	106
SAS	corn	81	109	52	84	55	91	55	93
Uruguay	corn	73	152	64	149	89	223	92	234

CAC	corn	60	8	77	24	37	-9	31	-14
Colombia	corn	57	59	58	59	24	18	23	15
Mexico	corn	42	34	51	42	34	25	33	24
SAN	corn	55	-55	70	-42	87	-40	89	-40

Table A-5. 2050 % change in beef and corn production volume relative to 2015 in all LAC economies, across all scenarios.

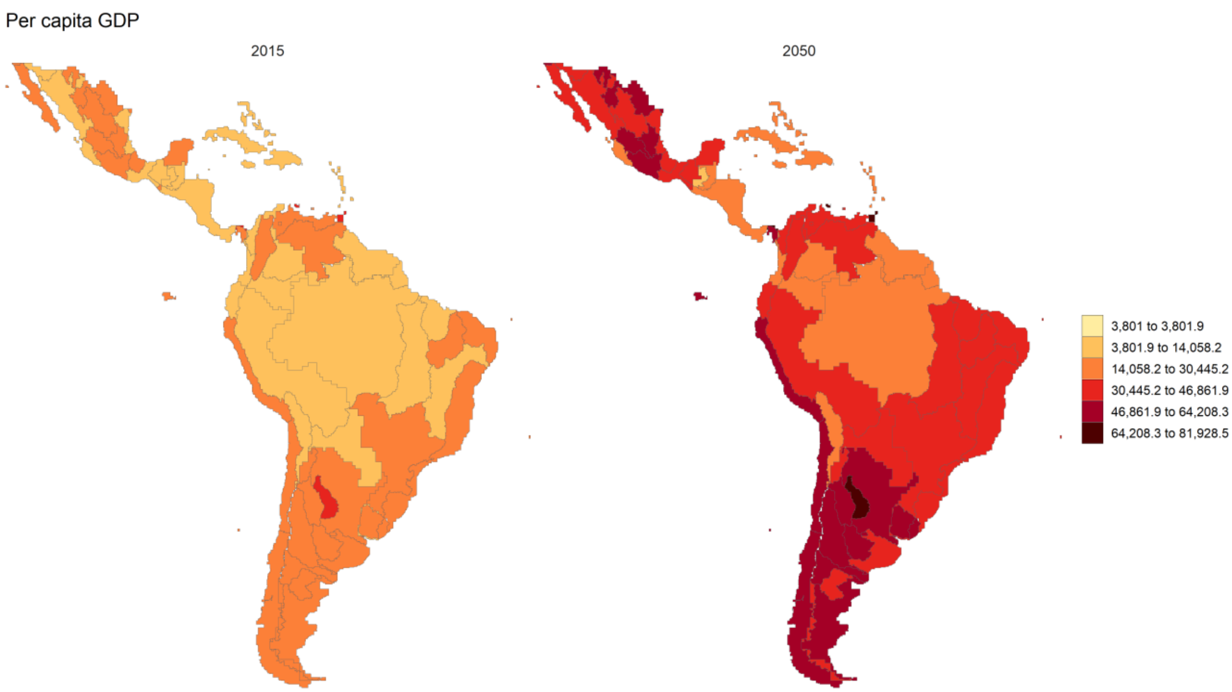


Figure A-11. SSP2 per capita GDP data (2020$/person) by water-economy region (WER) across LAC in 2015 and 2050. Data aggregated from gridded GDP and population from Murakami and Yamagata (2016).

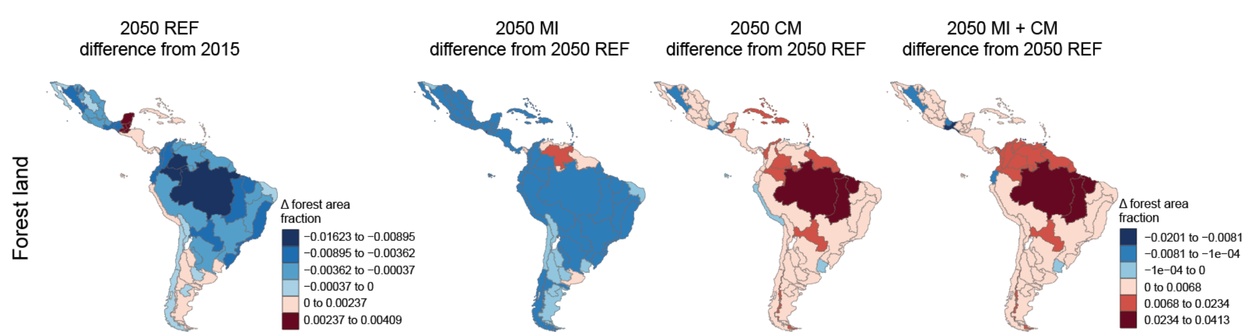


Figure A-12. Forest land by WER. Maps on the left show difference from 2015 under REF in 2050. Maps on the right show % change from REF under the MI, GHG, and MI + GHG scenarios in 2050.

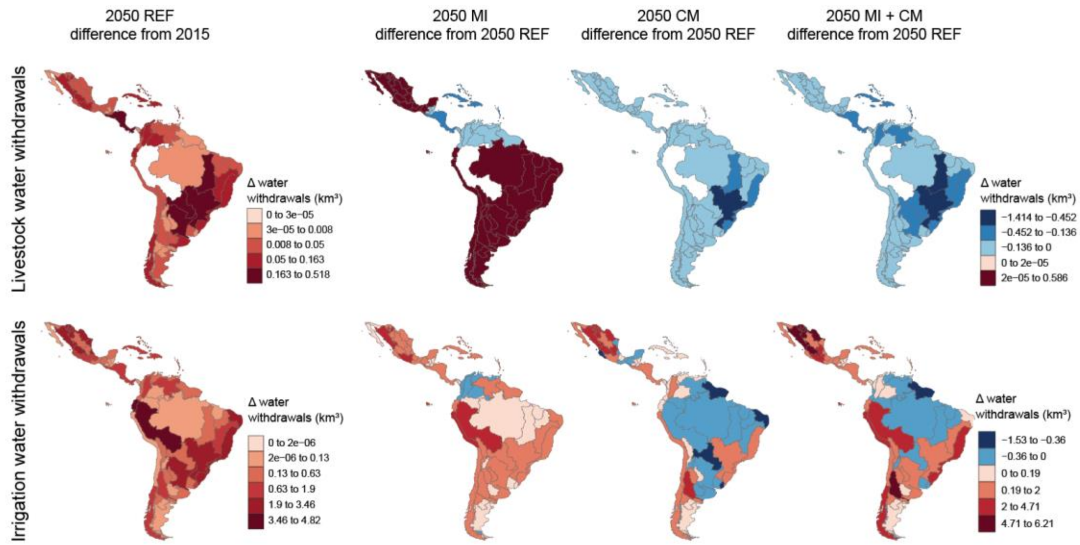


Figure A-13. a) Livestock water withdrawals by WER b) Irrigation water withdrawals by WER. Maps on the left show difference from 2015 under REF in 2050. Maps on the right show % change from REF under the MI, GHG, and MI + GHG scenarios in 2050.

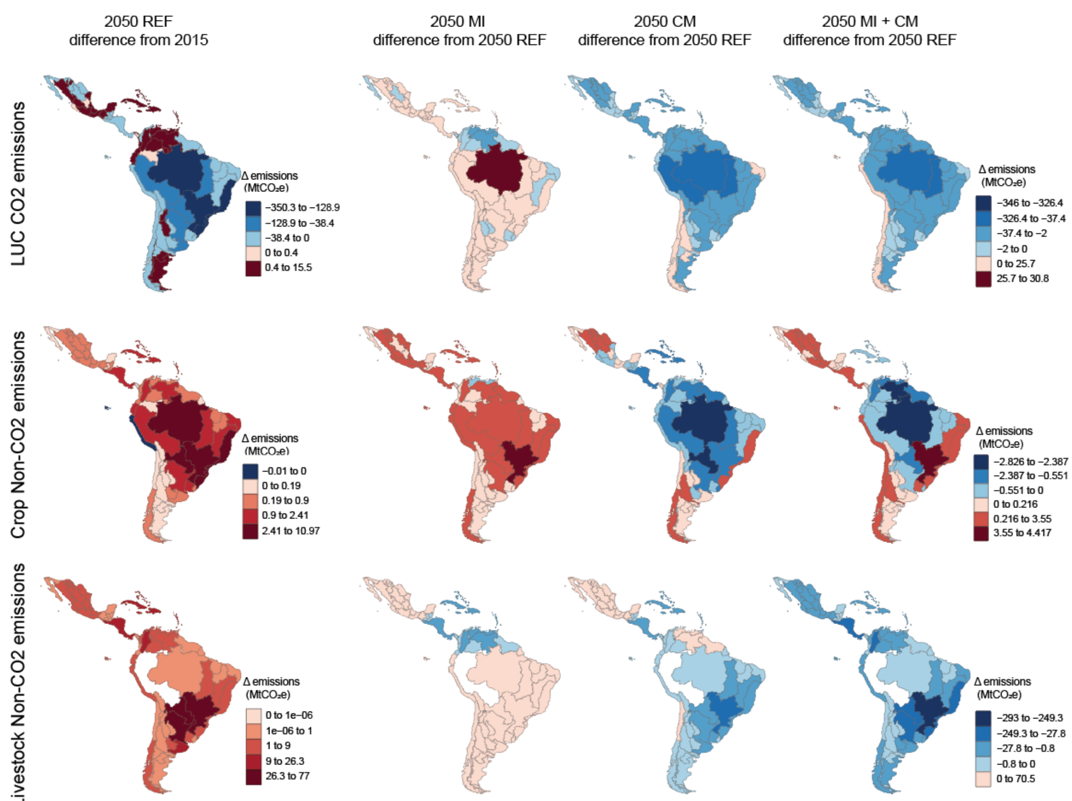


Figure A-14. a) LUC CO2 by WER b) Crop Non-CO2 by WER and c) Livestock Non-CO2 by WER. Maps on the left show difference from 2015 under REF in 2050. Maps on the right show % change from REF under the MI, GHG, and MI + GHG scenarios in 2050.

Appendix B: Supplementary material for Essay 2

B.1 Literature review

	Pipeline	**LNG**
Physical characteristics of transport process	Natural gas traded in gaseous form	Liquefaction: Natural gas is cooled, which reduces volume of gas by 600x Regasification: converted back to gaseous form at destination. Can use either land terminal or floating storage and regasification unit (FSRU) Easier and safer to transport
Scale of trade	Regional scale in regionally segmented markets	Global scale; can reach more widespread dispersed regions previously inaccessible to the gas market
Optimal distance	Cost-competitive at short-medium distances	Cost competitive only at long distances due to high upfront costs
Source/destination flexibility	Cost-competitive for inland destinations No flexibility in source and destination location; poses risks if supply and/or demand is altered; no alternatives in case of pipeline failures, which could cause supply interruptions Geological constraints on where pipelines can be placed	Flexibility in switching source and destination location Can use stranded assets of gas supply and then move to a different source
Market structure	Regional prices Historically, traded under long term firm contracts to manage risk and provide guarantee of return on investments	Regional prices and still often long-term contracts, but offers potential to move towards global price, based on supply and demand
Capital costs and project construction decisions	Long-term investment, built after careful evaluation of future demand	More capital intensive than pipeline, particularly export (liquefaction facilities), lead times longer
Operating decisions	Strong incentive to maximize utilization to have shorter payback period on capital and	

	better optimization of fixed operating costs	
Political considerations	Risks due to geopolitical shifts constraining supply	Less risky because source/destination can be flexibly switched, allowing for diversified supply

Table B-1. Characteristics of pipeline vs. LNG trade. (Paltsev, 2015; Jovanovic et al., 2019; Hafner and Luciani (eds.), 2022; Vivoda, 2019).

Author; Model	**Geographical scope**	**Representation of pipeline gas and LNG trade**	**Representation of natural gas supply and demand**	**Key insights**
Detailed natural gas sector models				
Egging et al. (2010); World Gas Model	Global	Country nodal LNG and pipeline trade, with detailed supply chain agents (e.g., producers, traders, liquefiers, regasifiers, storage operators, consumers).	Exogenously specified natural gas supply, competing technologies not represented. Sectoral demands modeled with linear functions.	Europe may expand pipeline import capacity, while LNG may play a major role in Asia.
Holz et al. (2015); Global Gas Model	Global	Country nodal LNG and pipeline trade, with detailed supply chain agents (e.g., producers, traders, liquefiers, regasifiers, storage operators, consumers).	Exogenously specified natural gas supply, competing technologies not represented. Sectoral demands modeled with linear functions.	Future of natural gas in a low carbon energy system is uncertain (could increase or decrease). Moderate global climate policy could have strong increase in global natural gas demand, while more ambitious climate policy could have moderate increase in global gas demand, decreasing in

				Europe and North America. Regardless of climate policy stringency, growing gas demand in Asia, and particularly LNG demand.
Egging-Bratseth et al. (2021); Global Gas Model	Global	Country nodal LNG and pipeline trade, with detailed supply chain agents (e.g., producers, traders, liquefiers, regasifiers, storage operators, consumers).	Exogenously specified natural gas supply, competing technologies not represented. Sectoral demands modeled with linear functions.	The interconnectedness of global gas markets due to an abundance of LNG import capacity allows for adjustments to global trade patterns that mitigate the consequences of regional disturbances. Europe is not an attractive market for US LNG, unless moderate support is provided. Asia offers higher prices for US LNG and draws substantially higher import volumes.
Meza et al. (2021); agent-based model	Global	Agent-based model of LNG market supply chain, including competition among various suppliers. Represents LNG	Exogenously specified natural gas supply, competing technologies not represented.	Qatar is the most competitive supplier, even when new LNG infrastructure comes online everywhere; The US is an emergent

		contracts and spot markets, as well as shipping routes and associated costs. Pipeline markets not represented.		competitor with multiple projects finding demand in all the LNG regions; Australia still highly depends on the Asian Pacific basin; Other smaller exporters would struggle to find importing markets but collectively would open new regional markets. Around 510+ MTPA of LNG trade by 2030.
Zhang et al. (2016)	China	Provincial nodal pipeline trade, with LNG import terminals at coastal nodes. International pipeline trade not modeled.	Natural gas supply only, competing technologies not represented. Demand for natural gas is modeled in aggregate (not by sector).	Pipeline imports replace LNG imports when international prices increase. High imports in China result in substantial pipeline infrastructure expansion in SW China regions.
Lau et al. (2022)	Europe	Linear model of the European network of transmission system operators for gas (ENTSO-G) pipeline network with gas supply/demand profiles from 2021 and current/planned pipeline and LNG infrastructure.	Competing electricity sector supply sector technologies represented. Exogenous gas demand reductions set by sector for each scenario.	Strategies for Europe to rapidly reduce reliance on Russian gas: increased pipeline gas and LNG imports from alternative sources, reduced gas demand in heating and industry, reduced gas-fired electricity generation, adopting flexible

				storage fill requirements
Multi-sectoral models				
IEA World Energy Outlook (2022)	Global	Global pipeline gas and LNG trade modeled.	Regional-level natural gas supply, in competition with other technologies. Multi-sectoral demand.	Higher European LNG demand, diverted gas from other importers in Asia. Not all Russian flows displaced from Europe will find demand in other markets. Rapid growth in natural gas demand draws to a close.
Shepard et al. (2022); MESSAGEix-GLOBIOM	Global	Pipeline gas in Europe only and LNG trade are represented bilaterally.	Regional-level natural gas supply, in competition with other technologies. Multi-sectoral demand.	Import tariffs have marginal effects on the trade network (size of trade and import/export regions). High import tariffs reduce emissions in importing region, but not globally. A carbon tax reduces size and changes trade linkages, improving energy security for importers.
Paltsev (2014); EPPA	Russia, connected to global markets	Gas is traded between each region (focuses on Russian export to other regions). LNG vs. pipeline exports are not	Regional-level natural gas supply, in competition with other technologies. Multi-sectoral demand.	Natural gas can still play a substantial role in Russian exports. Russia does not need new pipeline capacity to EU unless it wants to

		explicitly distinguished.		diversify supply routes. Asian markets are attractive for Russian gas, but cheap shale gas in China could compete. Europe's reliance on LNG imports increases, while it still maintains sizeable imports from Russia.
Feijoo et al. (2018); GCAM-USA coupled to North American Natural Gas Model (NANGAM)	North America, connected to global markets	Global LNG and regional pipeline trade through GCAM-USA North America pipeline investments and flows through NANGAM.	State-level (US) and regional-level (rest of world) natural gas supply, in competition with other technologies through GCAM-USA. Multi-sectoral demand through GCAM-USA.	Additional investments in US pipeline infrastructure are required to satisfy increasing natural gas demand. Geographic distribution of investments across the US is heterogeneous. Under transition to a low-carbon economy, there is risk of underutilization.
Pedersen et al. (2022); PyPSA-Eur-Sec	Europe	Copper-plate transport model for natural gas within Europe. International trade (beyond Europe) of pipeline gas and LNG is not modeled.	Country-level natural gas supply, in competition with other technologies. Multi-sectoral demand.	Ambitious climate action reinforces energy security. To make up for lack of Russian gas, faster integration of heat pumps and renewables is

		Instead, scenarios considered limited gas availability in Europe to the level excluding Russian pipeline gas imports. A sensitivity scenario considers expansion of LNG imports to allow for increased gas availability in Europe.		needed to maintain climate ambitions. Postponed phase-out of coal and additional biomass are cost-optimal to ensure energy security.
Mannhardt et al. (2023)	Europe	Pipeline network for Europe, along with LNG and pipeline imports into Europe. Other international flows not modeled.	European energy system model optimizes operation of gas, electricity, and heating sectors by country. Endogenous gas demand reductions allowed in electricity, heat, and industrial sectors.	Selfish behavior of Central European countries exacerbates energy scarcity for many SE European countries. Proactive collaborative energy savings and a mild winter can fully relieve the stress of the gas shortage. Diversification of gas imports leads to bottlenecks in the gas network, especially in SE Europe. Electricity generation is mostly shifted to coal-based power plants, causing

				higher carbon emissions.

Table B-2. Previous energy system modeling studies of natural gas trade. This table only includes studies that include some representation of global pipeline gas and LNG trade, even if the geographical focus is only on a single region.

IAM Model	**Energy commodities traded**	**Trade market resolution**
REMIND	Crude oil, natural gas, coal, biomass	Global pool
WITCH	Crude oil, natural gas, coal	Global pool
GCAM	Oil, natural gas, coal, biomass	Global pool
GCAM (this paper)	Oil, pipeline natural gas, liquefied natural gas, coal, biomass	Global pool for all fuels except pipeline gas, which is traded in 6 regional pools
MESSAGE	Crude oil, pipeline natural gas, liquefied natural gas, coal, liquefied coal, oil products, electricity, biofuels, hydrogen	Most fuels and carriers in global pool (including LNG); pipeline natural gas is traded bilaterally between certain regions
TIAM-ECN	Crude oil, natural gas, coal, biomass, biofuels, oil products	Bilateral
IMAGE	Crude oil, natural gas, coal, biomass, biofuels, hydrogen	Bilateral

Table B-3. Comparison of energy trade across integrated assessment models (IAMs). Table adapted from Jewell et al. (2016), with GCAM details added.

B.2 GCAM implementation

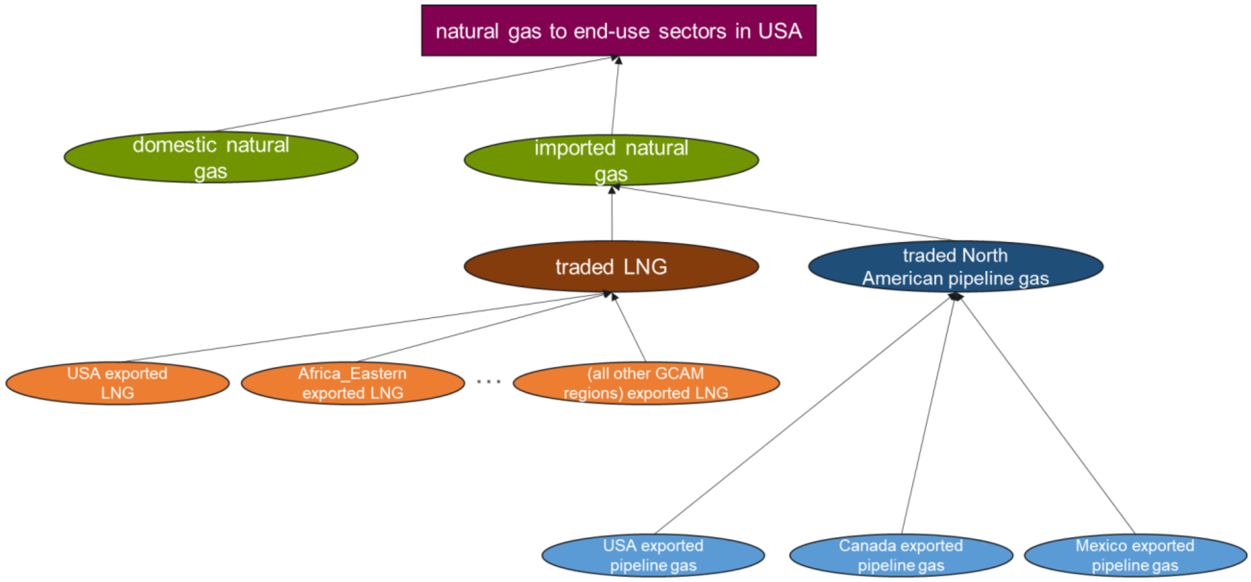


Figure B-1. Diagram of pipeline gas and LNG trade structure in GCAM. Example is given for the USA region.

Pipeline network bloc	**Regions that can export to pipeline network bloc**	**Regions that can import from pipeline network bloc**
North America (N. Amer)	Canada, USA, Mexico	Canada, USA, Mexico
Latin America (LA)	Argentina, Brazil, Central America and Caribbean, Colombia, South America_Northern, South America_Southern	Argentina, Brazil, Central America and Caribbean, Colombia, South America_Northern, South America_Southern
Europe (EUR)	EU-12, EU-15, Europe_Non_EU, European Free Trade Association	EU-12, EU-15, Europe_Non_EU, European Free Trade Association, Europe_Eastern
Russia+ (RUS)	Russia, Central Asia, Europe_Eastern	Russia, Central Asia, Europe_Eastern, EU-12, EU-15, Europe_Non_EU, European Free Trade Association, Middle East, China
Africa and Middle East (Afr_MidE)	Africa_Eastern, Africa_Northern, Africa_Southern, Africa_Western, Middle East, South Africa	Africa_Eastern, Africa_Northern, Africa_Southern, Africa_Western, Middle

		East, South Africa, EU-12, EU-15, Europe_Non_EU, Central Asia
Asia-Pacific (PAC)	Australia_NZ, China, India, Indonesia, Japan, Pakistan, South Asia, South Korea, Southeast Asia, Taiwan	Australia_NZ, China, India, Indonesia, Japan, Pakistan, South Asia, South Korea, Southeast Asia, Taiwan

Table B-4. Pipeline network blocs

	Cost component	2015	2020	2025	2030	2035	2040	2045	2050	2100
Reference	liquefaction	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03
LLS	liquefaction	1.03	1.03	0.95	0.87	0.76	0.68	0.61	0.53	0.53
Reference	shipping	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
LLS	shipping	0.65	0.65	0.57	0.49	0.46	0.42	0.38	0.34	0.34

Table B-5. Liquefaction and Shipping costs for LNG capacity under Reference vs. Low Liquefaction and Shipping cost (LLS) scenarios. All costs in 2020$/GJ.

Cost component	2015	2020	2025	2030	2035	2040	2045	2050	2100
regasification	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34
pipeline	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57

Table B-6. Regasification costs (for LNG capacity) and pipeline costs (for pipeline gas capacity) under all scenarios. All costs in 2020$/GJ.

Region Type	**GCAM Regions**	**Target**	**Constraint implementation in GCAM**
Developed countries, natural gas importers with sufficient resources	EU-12, EU-15, Europe_Eastern, Europe_Non_EU	Cut import dependence to 0 by 2030	Linear phase-out from 2020 gross imports to 0 by 2030
Developed countries, natural gas importers, low natural gas resources	Japan, South Korea, Taiwan	Maintain current import dependence throughout the century	Maintain share of gross imports in total consumption at historical levels
Developing countries,	Brazil, China, India, Pakistan, Southeast Asia,	Maintain current import	Maintain share of gross imports in total

natural gas importers	Mexico, South Africa	dependence throughout the century	consumption at historical levels
Natural gas exporters	USA, Africa_Eastern, Africa_Northern, Africa_Southern, Africa_Western, Australia_NZ, Canada, Central America and Caribbean, Central Asia, European Free Trade Association, Indonesia, Middle East, Russia, South America_Southern, South America_Northern, South Asia, Colombia, Argentina	Zero out any imports	Linear phase-out from 2020 gross imports to 0 by 2030

Table B-7. Details of Limited Trade (LT) scenarios construction.

Region	2015	2020	2025	2030	2035	2040	2045	2050
Africa_Eastern	2.93E+08	3.28E+08	3.63E+08	3.99E+08	4.34E+08	4.68E+08	5.00E+08	5.29E+08
Africa_Northern	1.85E+08	1.97E+08	2.07E+08	2.17E+08	2.25E+08	2.32E+08	2.39E+08	2.44E+08
Africa_Southern	1.60E+08	1.80E+08	2.00E+08	2.20E+08	2.40E+08	2.60E+08	2.79E+08	2.97E+08
Africa_Western	4.78E+08	5.37E+08	6.00E+08	6.64E+08	7.30E+08	7.96E+08	8.61E+08	9.24E+08
Argentina	4.31E+07	4.46E+07	4.60E+07	4.73E+07	4.84E+07	4.93E+07	5.01E+07	5.06E+07
Australia_NZ	2.85E+07	3.06E+07	3.27E+07	3.46E+07	3.64E+07	3.82E+07	4.00E+07	4.17E+07
Brazil	2.04E+08	2.12E+08	2.19E+08	2.24E+08	2.28E+08	2.31E+08	2.33E+08	2.33E+08
Canada	3.60E+07	3.79E+07	3.98E+07	4.16E+07	4.32E+07	4.47E+07	4.63E+07	4.78E+07
Central America and Caribbean	8.62E+07	9.04E+07	9.42E+07	9.76E+07	1.00E+08	1.03E+08	1.05E+08	1.06E+08
Central Asia	8.81E+07	9.15E+07	9.43E+07	9.64E+07	9.79E+07	9.91E+07	9.98E+07	1.00E+08
China	1.41E+09	1.43E+09	1.44E+09	1.43E+09	1.42E+09	1.39E+09	1.36E+09	1.31E+09
Colombia	4.75E+07	5.03E+07	5.29E+07	5.52E+07	5.72E+07	5.90E+07	6.04E+07	6.16E+07
EU-12	1.01E+08	1.00E+08	9.99E+07	9.89E+07	9.76E+07	9.62E+07	9.47E+07	9.32E+07
EU-15	4.04E+08	4.11E+08	4.17E+08	4.23E+08	4.28E+08	4.33E+08	4.37E+08	4.41E+08
Europe_Eastern	5.84E+07	5.69E+07	5.55E+07	5.42E+07	5.31E+07	5.21E+07	5.13E+07	5.04E+07
Europe_Non_EU	1.01E+08	1.05E+08	1.08E+08	1.12E+08	1.14E+08	1.16E+08	1.18E+08	1.19E+08
European Free Trade Association	1.39E+07	1.44E+07	1.49E+07	1.54E+07	1.59E+07	1.64E+07	1.68E+07	1.73E+07

India	1.31E+09	1.39E+09	1.46E+09	1.53E+09	1.59E+09	1.65E+09	1.70E+09	1.74E+09
Indonesia	2.58E+08	2.69E+08	2.78E+08	2.85E+08	2.91E+08	2.94E+08	2.96E+08	2.96E+08
Japan	1.28E+08	1.27E+08	1.25E+08	1.22E+08	1.19E+08	1.16E+08	1.13E+08	1.10E+08
Mexico	1.22E+08	1.28E+08	1.34E+08	1.39E+08	1.43E+08	1.47E+08	1.49E+08	1.51E+08
Middle East	2.40E+08	2.63E+08	2.85E+08	3.06E+08	3.26E+08	3.46E+08	3.63E+08	3.79E+08
Pakistan	1.99E+08	2.18E+08	2.35E+08	2.52E+08	2.67E+08	2.81E+08	2.95E+08	3.07E+08
Russia	1.45E+08	1.44E+08	1.43E+08	1.42E+08	1.41E+08	1.40E+08	1.39E+08	1.39E+08
South Africa	5.54E+07	5.78E+07	6.00E+07	6.18E+07	6.33E+07	6.46E+07	6.57E+07	6.65E+07
South America_Northern	3.17E+07	3.37E+07	3.56E+07	3.73E+07	3.89E+07	4.02E+07	4.12E+07	4.21E+07
South America_Southern	8.56E+07	8.96E+07	9.32E+07	9.62E+07	9.87E+07	1.01E+08	1.02E+08	1.03E+08
South Asia	2.40E+08	2.56E+08	2.73E+08	2.88E+08	3.01E+08	3.14E+08	3.24E+08	3.33E+08
South Korea	5.08E+07	5.13E+07	5.16E+07	5.16E+07	5.13E+07	5.05E+07	4.94E+07	4.80E+07
Southeast Asia	4.13E+08	4.33E+08	4.51E+08	4.66E+08	4.79E+08	4.89E+08	4.95E+08	4.99E+08
Taiwan	2.36E+07	2.36E+07	2.36E+07	2.36E+07	2.36E+07	2.36E+07	2.36E+07	2.36E+07
USA	3.24E+08	3.37E+08	3.50E+08	3.62E+08	3.73E+08	3.84E+08	3.94E+08	4.03E+08

Table B-8. Population by GCAM regions (2015-2050).

Region	2015	2020	2025	2030	2035	2040	2045	2050
Africa_Eastern	271180	334530	427332	574544	764608	1018878	1354636	1790046
Africa_Northern	748130	922277	1121400	1404045	1716681	2063691	2444284	2854340
Africa_Southern	277825	308792	376958	475157	591208	745183	951236	1222392
Africa_Western	893584	1010474	1235377	1686622	2265662	3025561	4015643	5291044
Argentina	541176	535365	633120	737968	847336	957080	1065643	1177173
Australia_NZ	1812519	2062028	2349779	2638675	2932397	3246090	3585723	3929505
Brazil	2757440	2850640	3207776	3661545	4097293	4545716	4997536	5443045
Canada	2125943	2331097	2538038	2788924	3066288	3364068	3667552	3966120
Central America and Caribbean	468506	537139	629250	746765	877179	1026643	1196283	1384750
Central Asia	462327	559567	694001	856079	1018060	1176710	1324533	1453408
China	10855536	14793748	19308553	23778125	27711349	30929441	33789967	36114145
Colombia	423578	482809	575447	675172	787301	914244	1053866	1206220
EU-12	1713330	2060419	2351514	2642518	2931360	3207919	3458394	3693869
EU-15	19308553	21096382	22705428	24493257	26281086	28426480	30750658	32896053
Europe_Eastern	222831	250870	290247	340551	393448	447308	499845	550934
Europe_Non_EU	1449638	1652199	1937148	2252003	2575171	2919042	3272496	3632225
European Free Trade Association	1316495	1433512	1555864	1683289	1817078	1965557	2129930	2314130
India	2705539	3870864	5499719	7139570	9005688	11141732	13517399	16105586
Indonesia	1165378	1496987	1939204	2497204	3102598	3771729	4474954	5195467
Japan	7071614	7415378	7649083	8007543	8274752	8486413	8716953	8940057
Mexico	1442921	1601591	1828949	2118452	2429070	2758406	3115292	3506826
Middle East	2982492	3298705	3741336	4486861	5270913	6102540	6949845	7800459
Pakistan	250505	307280	356094	452405	575084	731621	925396	1159007
Russia	1955831	2108941	2319136	2682029	3028904	3342364	3597523	3804786
South Africa	494020	520752	579961	688486	801650	920703	1042923	1167077

South America_Northern	358376	145979	143440	167303	193693	222109	253314	287240
South America_Southern	749926	860194	1014282	1211100	1416079	1639400	1880510	2136366
South Asia	328195	437326	583243	753482	946632	1176341	1444469	1755637
South Korea	1496424	1718999	1983435	2248606	2485154	2691916	2873506	3026347
Southeast Asia	1842858	2322372	2919239	3564681	4253978	5016451	5844860	6729048
Taiwan	600276	677469	757525	825439	889538	947991	993098	1021776
USA	19844901	21990296	23956908	26281086	28426480	30571875	32538487	34326316

Table B-9. GDP (2020$, thousands) by GCAM region (2015-2050).

Aggregated Region	GCAM Regions
USA	USA
Middle East	Middle East
Russia	Russia
EUR	EU-12, EU-15, Europe_Non_EU, European Free Trade Association
SE Asia	Indonesia, Southeast Asia
CAN + MEX	Canada, Mexico
Africa	Africa_Eastern, Africa_Northern, Africa_Southern, Africa_Western, South Africa
C. Asia + E. Eur	Central Asia, Eastern Europe
LAC	Argentina, Brazil, Central America and Caribbean, Colombia, South America_Northern, South America_Southern
China	China
Australia+NZ	Australia_NZ
S. Asia	Pakistan, South Asia
India	India
E. Asia	Japan, South Korea, Taiwan

Table B-10. Aggregated region groupings as shown on figures.

B.3 Additional results (figures and tables)

region	Reference	Reference_LLS	Reference_LT	Transition	Transition_LLS	Transition_LT
Africa_Eastern	14.22	13.45	16.04	11.62	10.68	16.69
Africa_Northern	4.83	4.90	4.42	4.02	4.04	3.57
Africa_Southern	11.76	11.32	12.65	10.00	9.70	10.73
Africa_Western	8.51	8.49	9.32	7.96	7.93	8.68
Argentina	8.27	8.21	8.81	7.89	7.84	8.21
Australia_NZ	5.55	5.58	5.48	5.49	5.49	5.38
Brazil	11.15	11.04	11.91	10.16	9.84	11.23
Canada	5.03	5.22	4.61	4.30	4.45	3.75
Central America and Caribbean	6.20	6.30	5.91	5.15	5.22	4.88
Central Asia	5.60	5.61	5.71	5.01	5.01	5.06
China	10.03	10.00	10.48	9.16	9.08	9.98

Colombia	8.82	8.61	9.81	8.11	7.94	8.85
EU-12	6.21	6.31	8.07	5.13	5.14	6.28
EU-15	5.96	5.94	6.83	5.36	5.28	5.38
Europe_Eastern	4.93	5.02	5.12	4.61	4.63	4.69
Europe_Non_EU	9.96	9.87	14.77	8.31	8.13	17.14
European Free Trade Association	5.11	5.42	4.42	4.20	4.46	3.71
India	7.32	7.26	7.44	6.97	6.89	7.09
Indonesia	6.58	6.63	6.55	5.20	5.24	4.93
Japan	8.06	8.00	7.86	7.57	7.52	7.06
Mexico	8.22	8.19	8.84	7.58	7.58	8.54
Middle East	4.06	4.15	3.93	3.34	3.42	3.19
Pakistan	10.60	10.48	11.44	8.97	8.75	10.44
Russia	5.73	5.67	5.31	5.07	5.02	4.80
South Africa	8.39	8.46	7.20	7.49	7.33	6.62
South America_Northern	7.75	7.72	7.96	7.37	7.35	7.42
South America_Southern	6.47	6.58	6.44	5.59	5.60	5.55
South Asia	7.93	7.96	7.71	8.94	8.88	8.76
South Korea	10.25	9.73	7.07	7.04	7.04	7.00
Southeast Asia	7.09	7.13	7.19	6.92	6.84	7.13
Taiwan	9.64	9.50	8.30	7.77	7.67	6.91
USA	3.53	3.83	3.26	2.94	3.04	2.79

Table B-11. Regional natural gas producer prices in 2050 across scenarios (2020$).

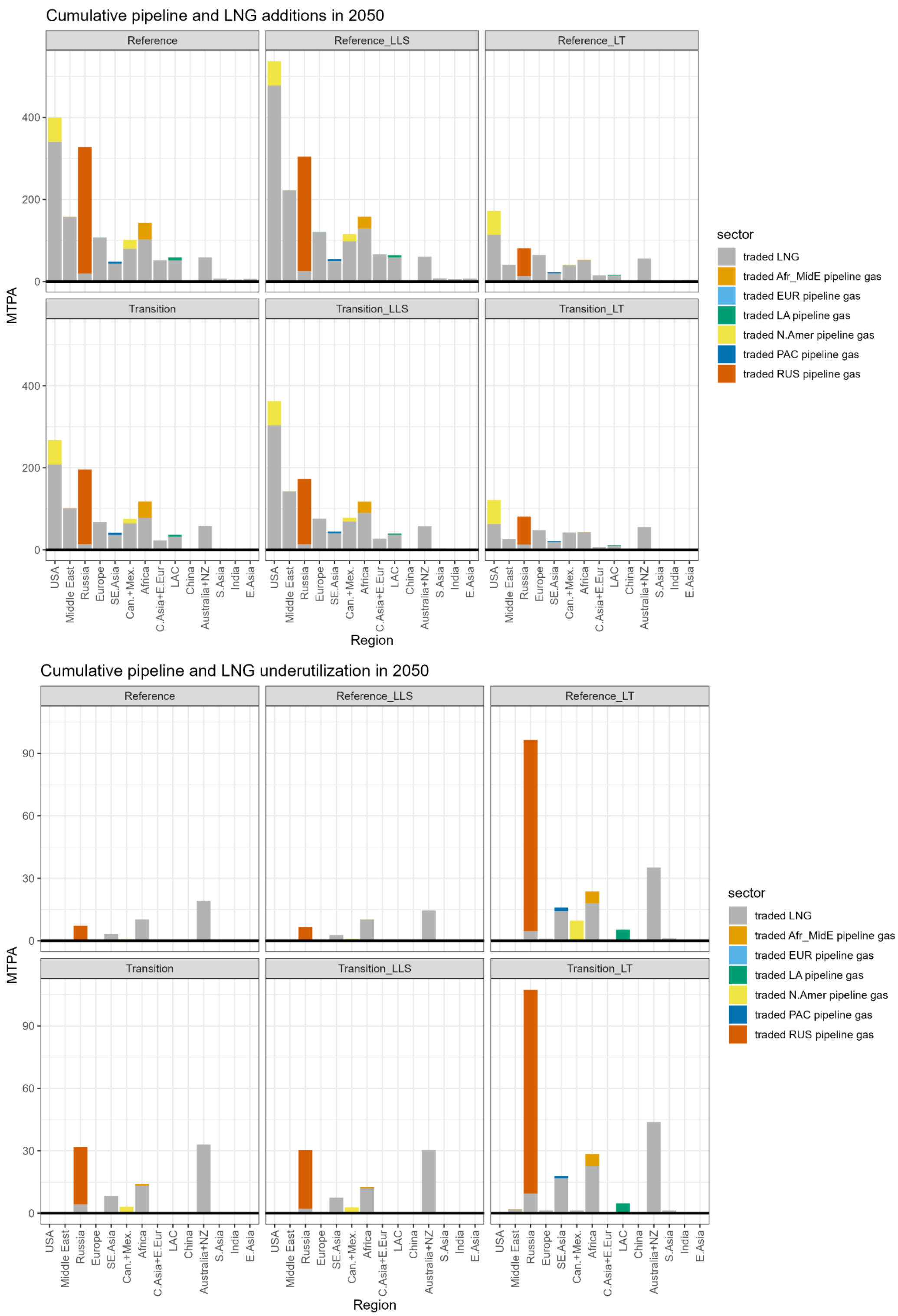


Figure B-2. Pipeline and LNG export capacity additions and underutilization by aggregated region. A, top). 2020-2050 cumulative new export capacity additions; B, bottom). 2020-2050 cumulative export capacity underutilization. MTPA = million tons per annum.

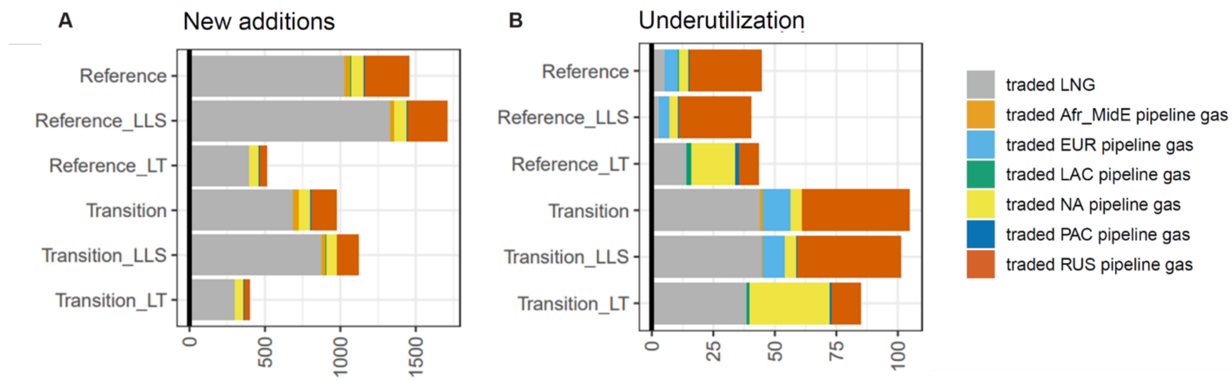
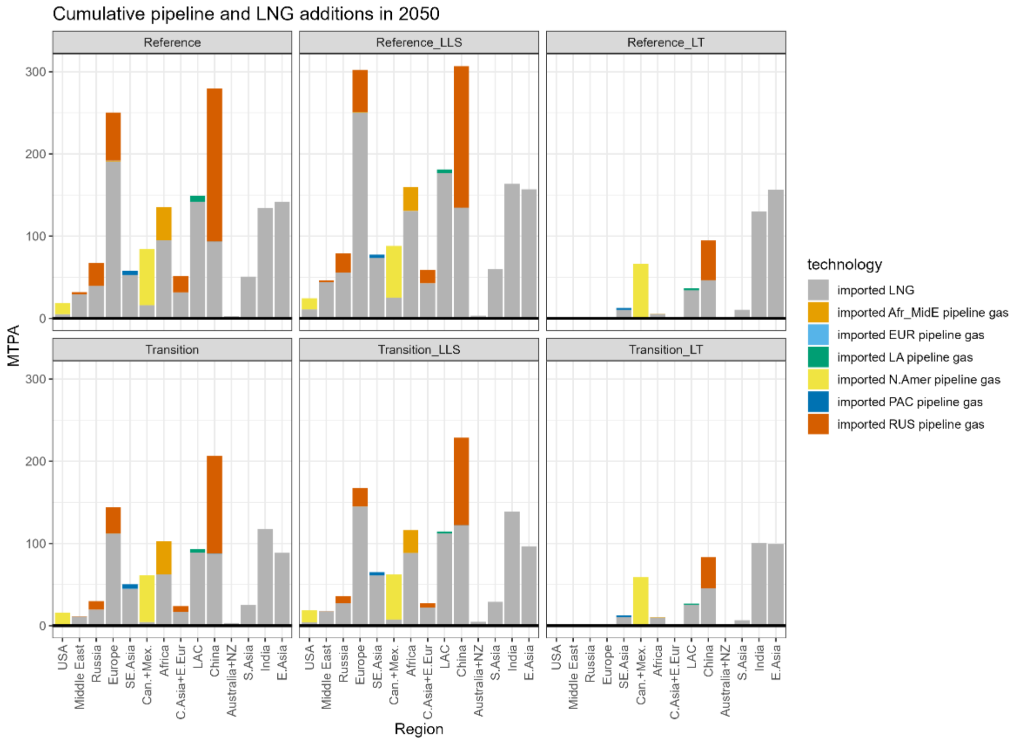


Figure B-3. Global pipeline and LNG import capacity additions and underutilization. A) 2020-2050 cumulative new import capacity additions, B) 2020-2050 cumulative import capacity underutilization. MTPA = million tons per annum.



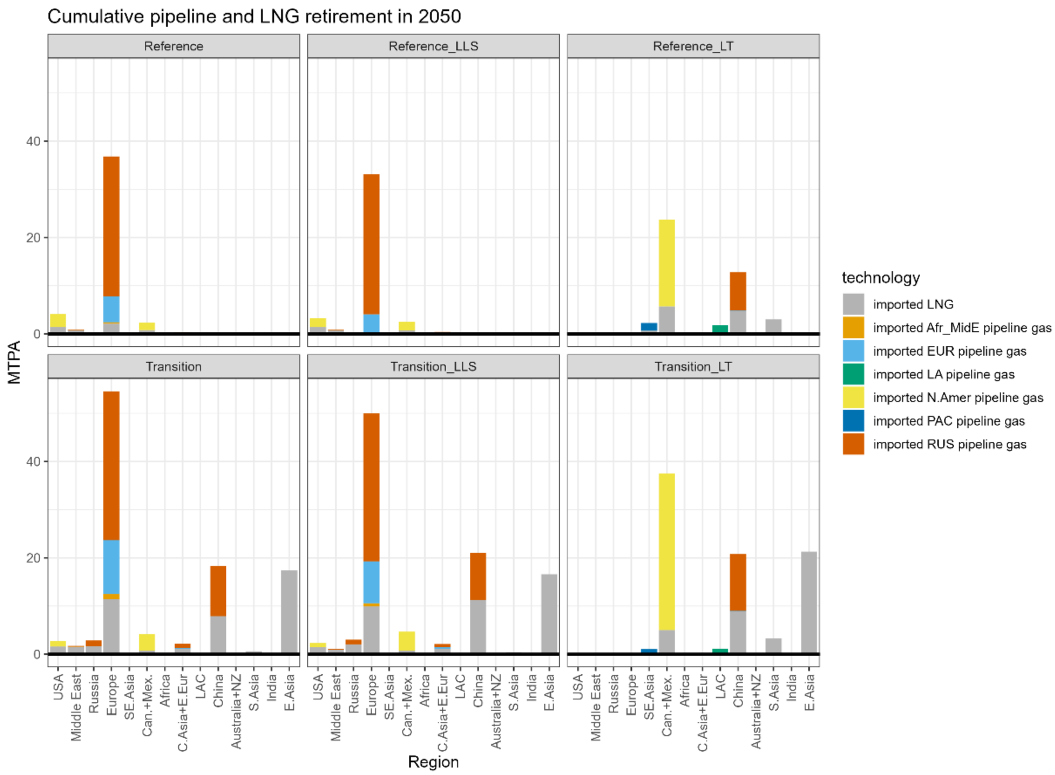


Figure B-4. Pipeline and LNG import capacity additions and underutilization by aggregated region. A, top). 2020-2050 cumulative new import capacity additions; B, bottom). 2020-2050 cumulative export capacity underutilization. MTPA = million tons per annum.

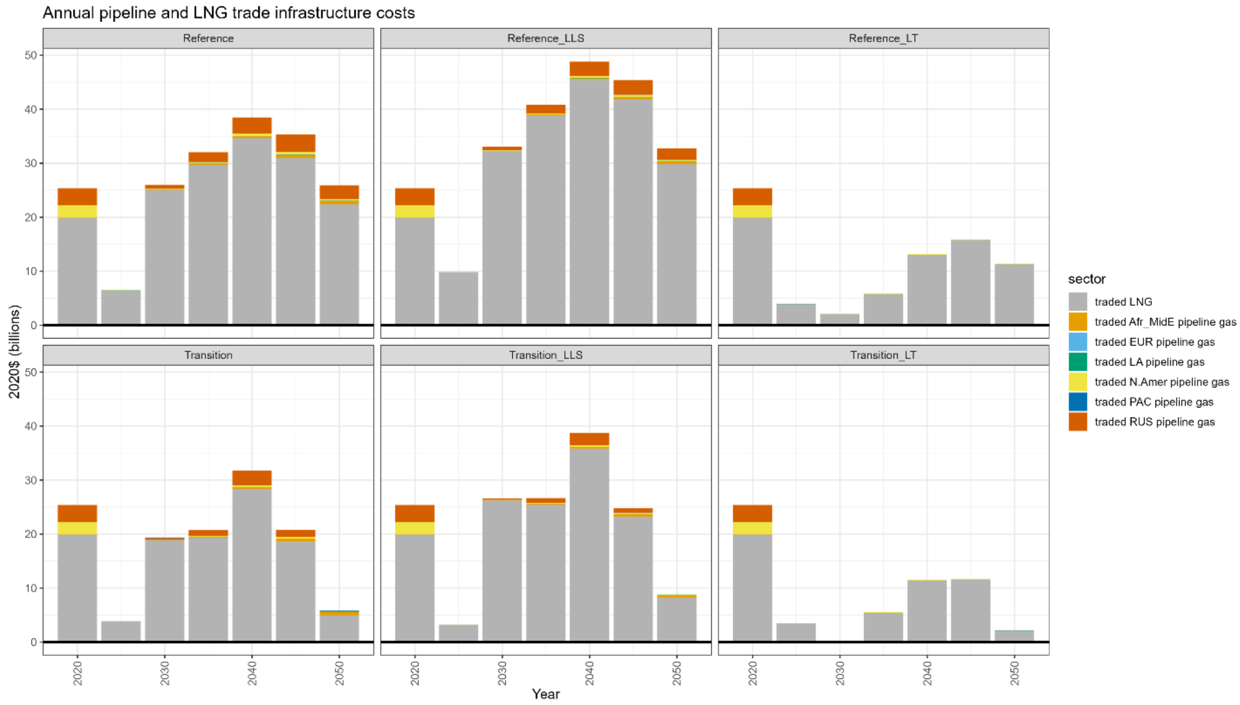


Figure B-5. Annual global pipeline and LNG trade capital infrastructure costs. Annual global investments in LNG and pipeline infrastructure range from $183 million-$49 billion ($2020 USD) across time periods and scenarios, ranging from 0.0001-0.03% of total global GDP across scenarios and years. Annual costs are calculated by multiplying new additions by GCAM per unit capital costs, as used in the Reference scenario (see **Tables S4 and S5**) and dividing by the fixed charge rate of 0.13 and 5 (to annualize over 5-year time periods). LNG infrastructure costs (liquefaction, shipping, and regasification) have been benchmarked to and fall in the middle of the range of estimates from Songhurst et al., 2018; Egging and Holz, 2019; Kavalov et al., 2009. Pipeline costs are derived from EIA data (EIA, 2021).

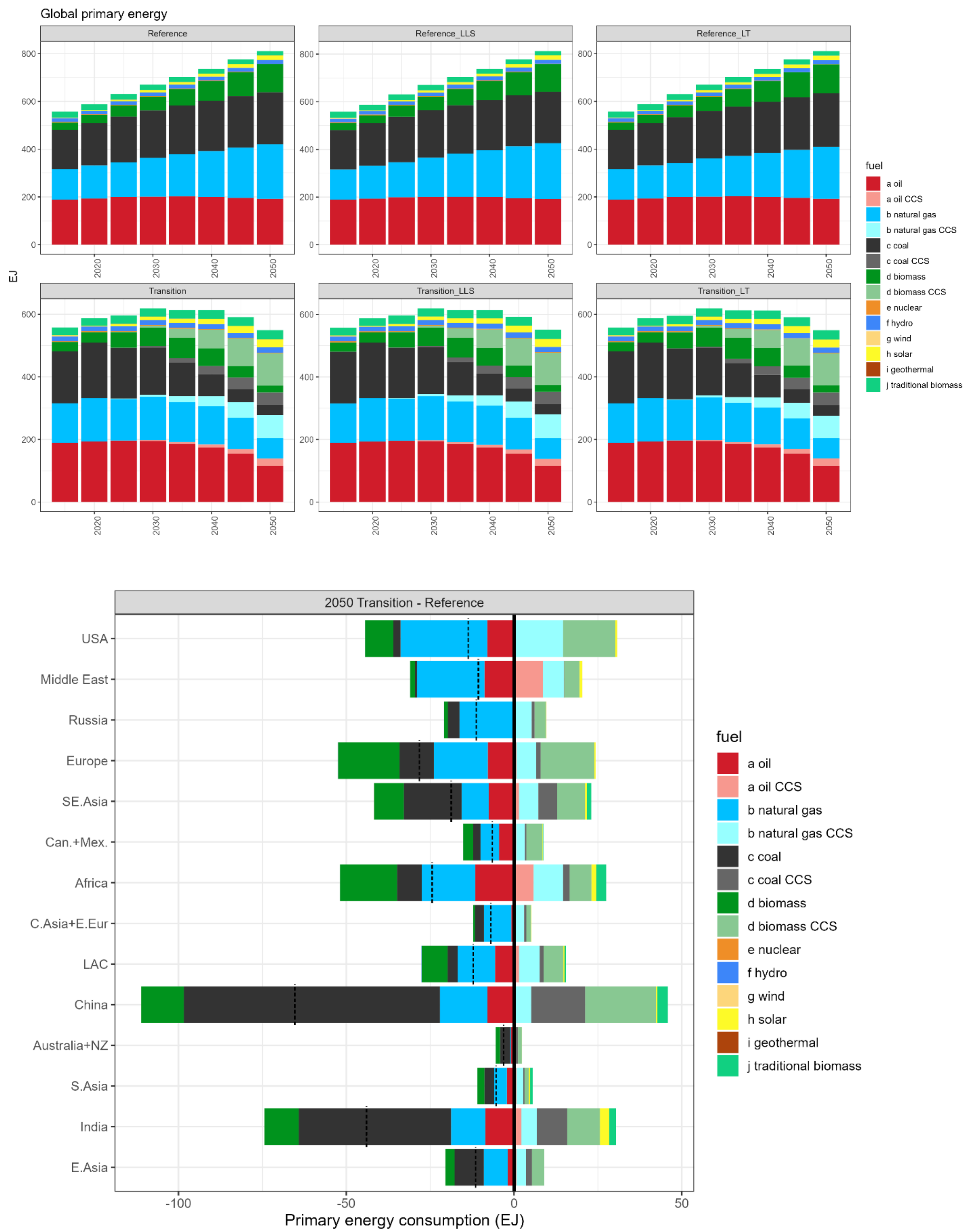


Figure B-6. A, top). Global primary energy consumption across scenarios (2015-2050). B, bottom). Change in primary energy consumption between Transition and Reference scenarios across aggregated GCAM regions in 2050.

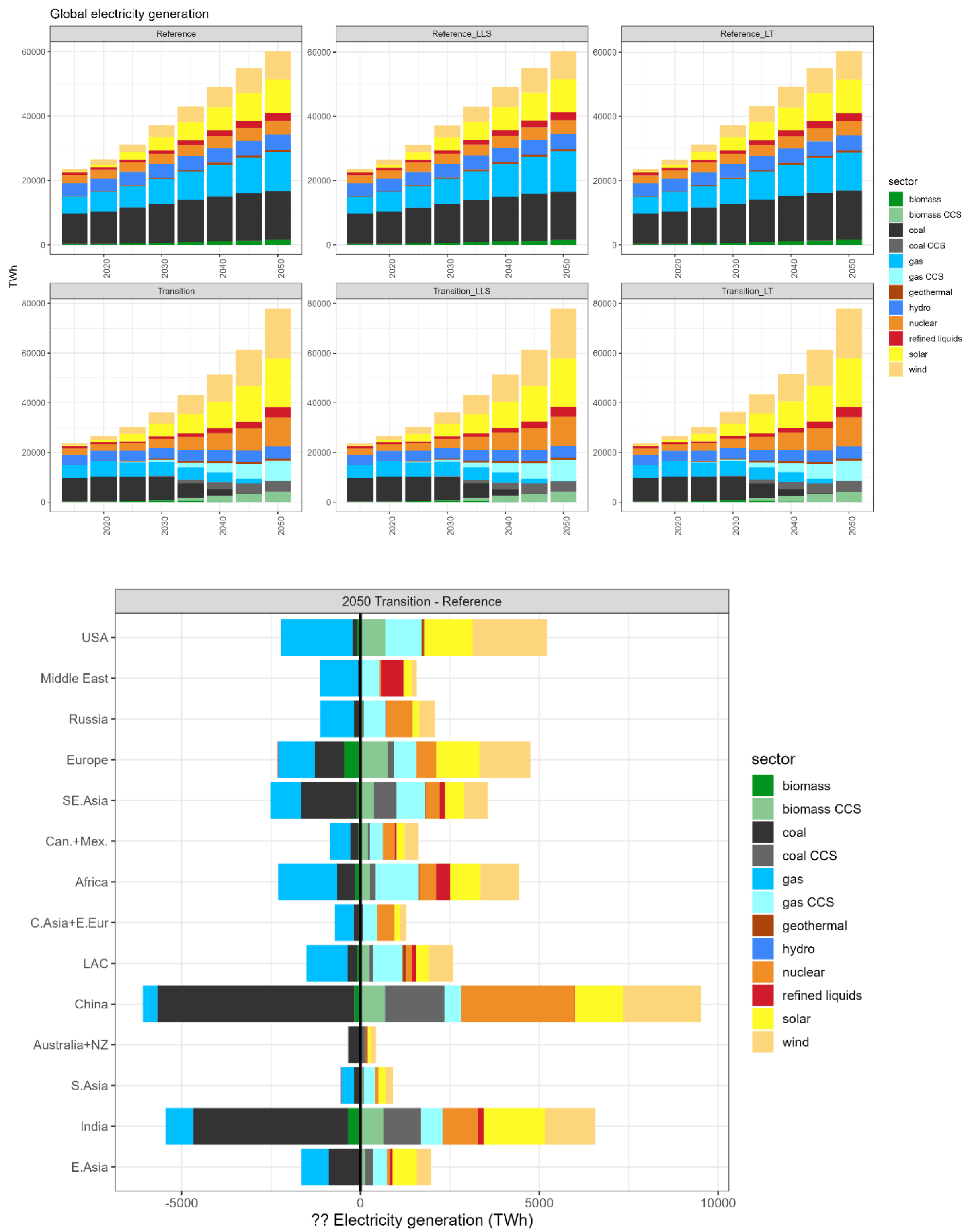


Figure B-7. A, top). Global electricity generation across scenarios (2015-2050). B, bottom). Change in electricity generation between Transition and Reference scenarios across aggregated GCAM regions in 2050.

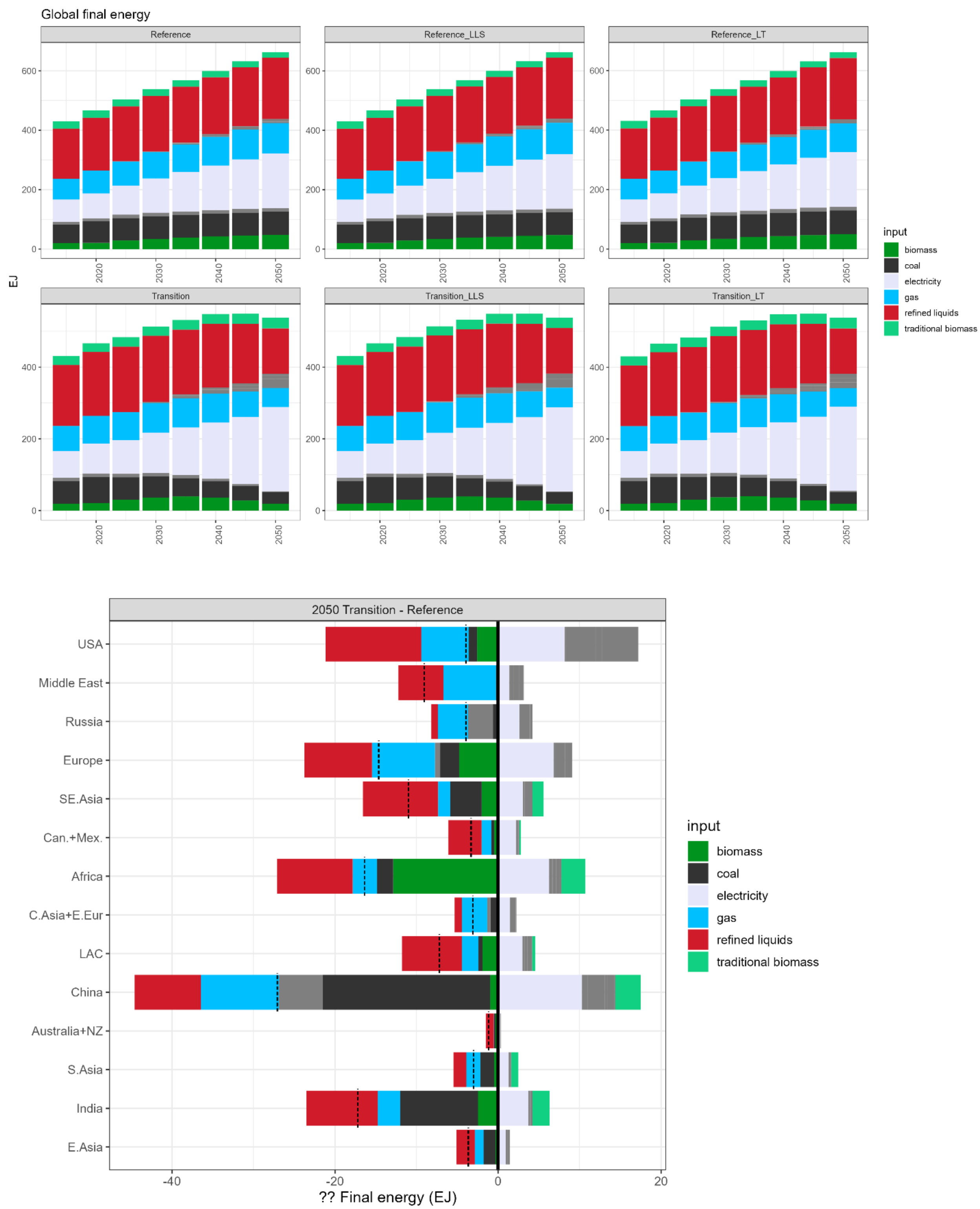


Figure B-8. A, top). Global final energy across scenarios (2015-2050). B, bottom.) Change in electricity generation between Transition and Reference scenarios across aggregated GCAM regions in 2050.

Comparison of results with the literature

The comparison figures with the literature highlight that our projections of natural gas trade (both through pipelines and as LNG) are higher than projections in IEA's WEO scenarios **(Figure B-9)**. However, our global natural gas consumption trends under both Reference and Transition pathways **(Figure B-12)** fall well within the range of natural gas consumption trends of scenarios in the IPCC AR6 database and are close to trends in Institute of Energy Economics of Japan (IEEJ) scenarios, which the IEA WEO scenarios were benchmarked to in the "Outlooks for gas markets and investment report" (IEA, 2023). Our Reference scenario aligns relatively well with the IEEJ-REF pathway, and our Transition scenario has lower natural gas consumption than the IEEJ-Advanced Technologies Scenario (IEEJ-ATS). This makes sense, given that the IEEJ-ATS introduces low- and zero-emission technologies and strengthens energy and environmental policies but does not achieve each country's carbon neutrality declaration. Developing countries continue to use fossil fuels to meet demand, and natural gas plays a significant role in IEEJ-ATS. Our Transition scenario is more ambitious than the IEEJ-ATS, in achieving global net zero CO2 emissions by 2050 and close to the IEA Announced Policies Scenario (APS) which assumes that all net zero targets are met on time, but not as ambitious as the IEA Net Zero Emissions Scenario (NZE), which assumes a 1.5C compatible pathway. In terms of global FFI CO2 emissions **(Figure B-13),** our Transition scenario is well within range of 1.5-2C pathways in the IPCC AR6 database and is close to IEA WEO's APS scenario in terms of 2050 FFI CO2 emissions, despite having higher natural gas consumption. Our scenarios have relatively high levels of natural gas with CCS use in the Transition scenarios **(Figure B-6)** while the WEO APS and NZE scenarios simulate very little gas CCS, which explains this finding. In our Transition scenario, nearly all gas generation in the power sector uses CCS by 2050 **(Figure B-7).**

Consistent with the global trends, our results project roughly higher levels of natural gas production and consumption than the WEO results. However, the WEO projects higher levels of natural gas production than our results in key producing regions: Australia_NZ, Middle East, and the USA, particularly in the near term **(Figures B-10 and B-11).**

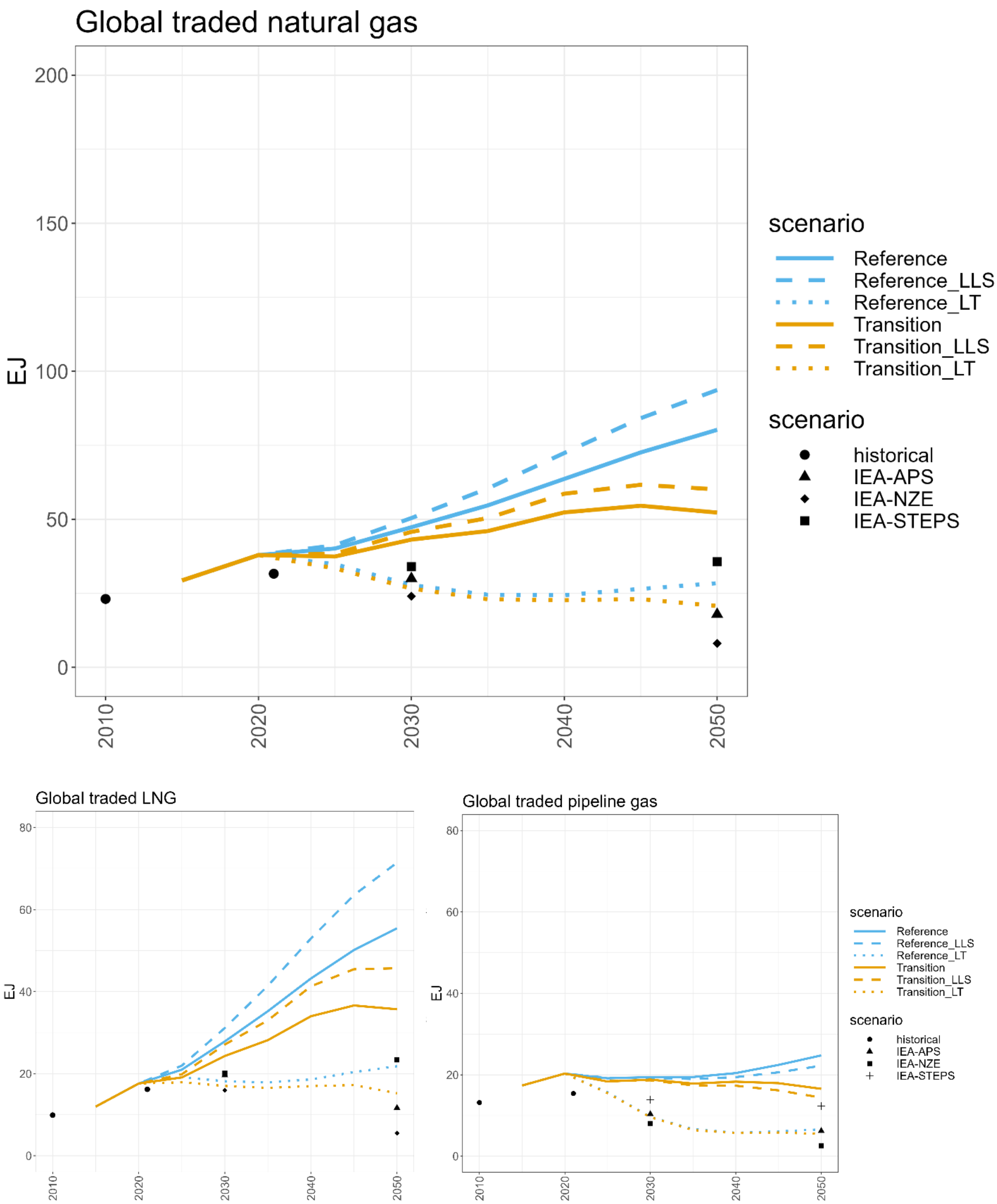


Figure B-9. A, top). Global traded natural gas, B, bottom left). Global traded LNG, C, bottom right). Global traded pipeline gas comparisons with IEA WEO 2022. IEA-APS = Announced Pledges Scenario, IEA-NZE = Net-Zero Emissions by 2050 Scenario, IEA-STEPS = Stated Policies Scenario.

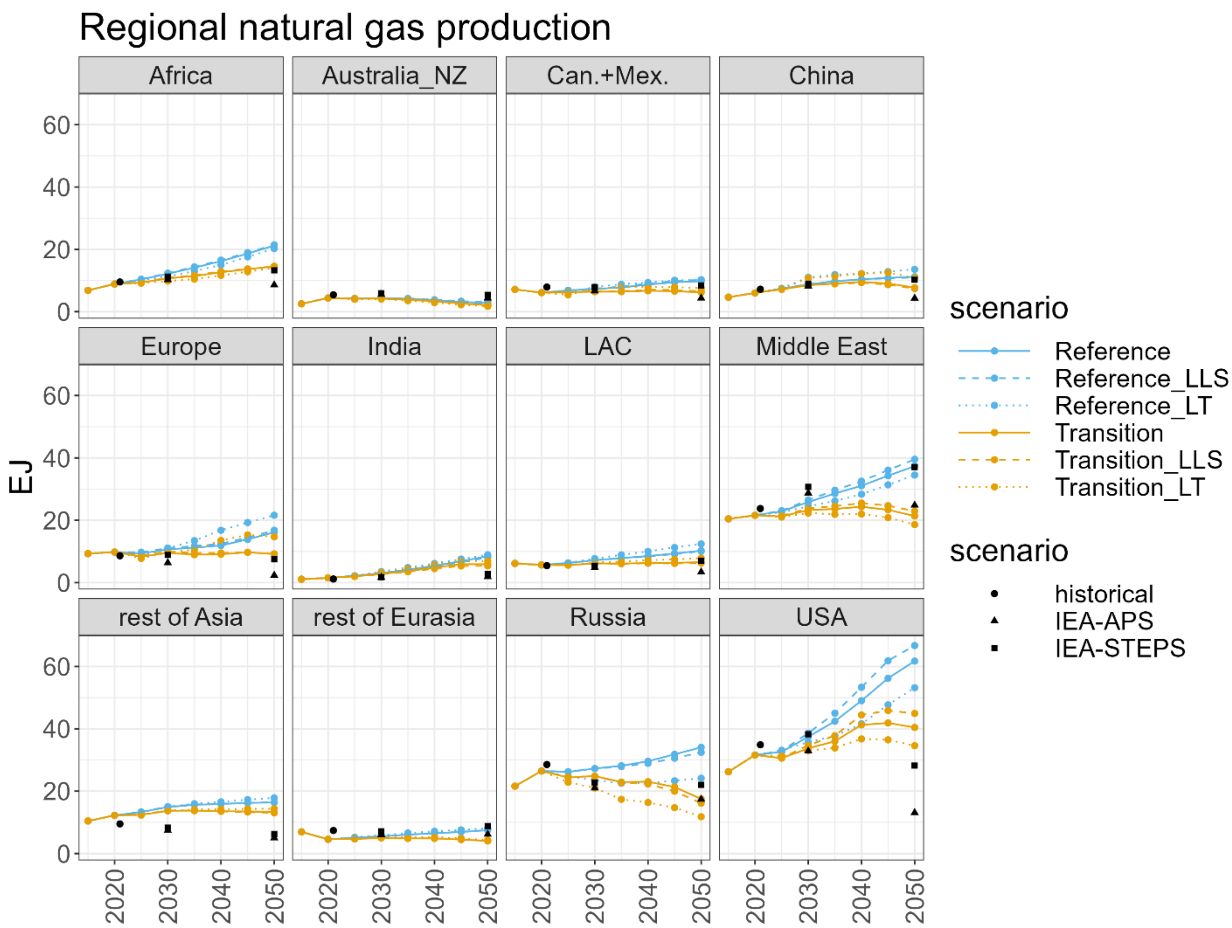


Figure B-10. Regional natural gas production comparisons with IEA WEO 2022. IEA-APS = Announced Pledges Scenario, IEA-STEPS = Stated Policies Scenario.

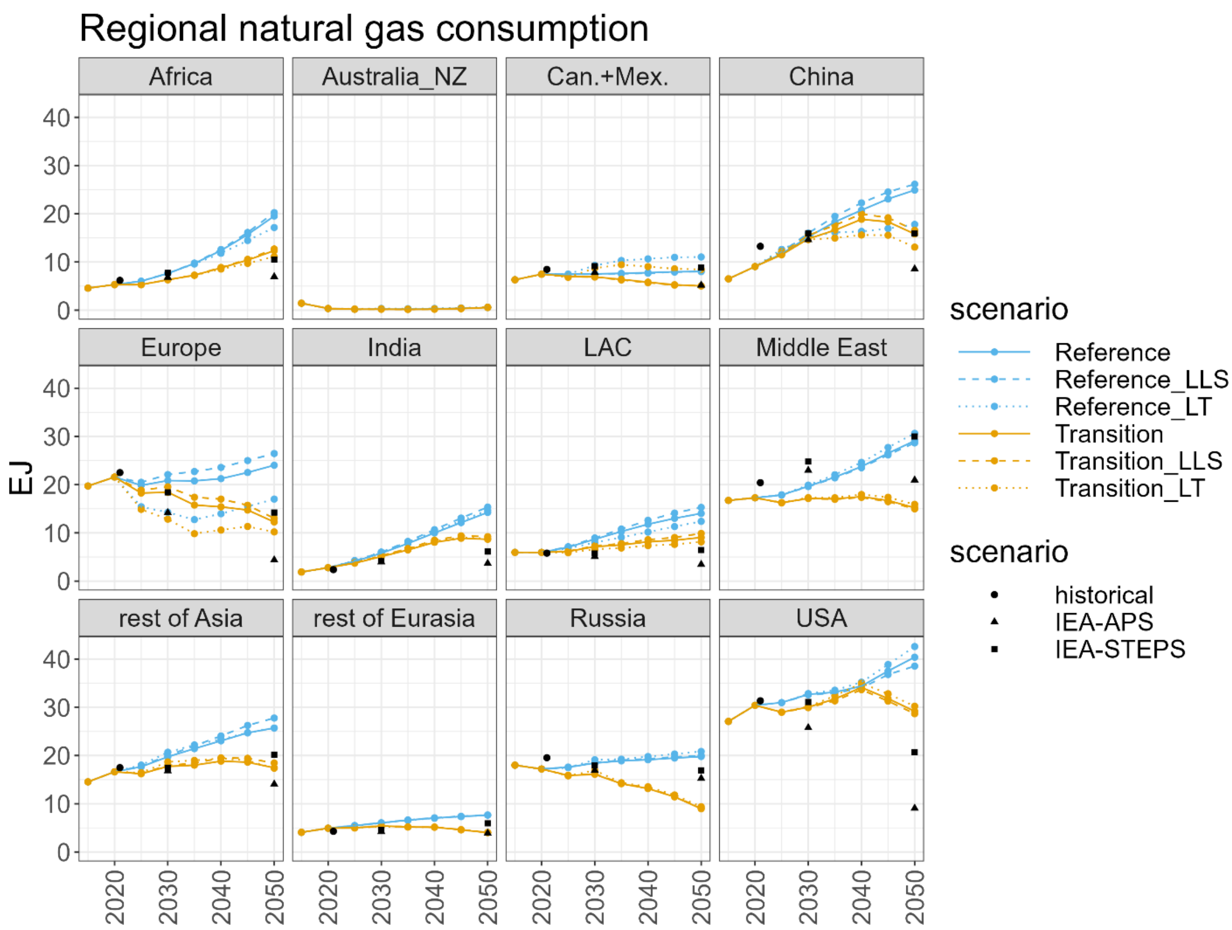


Figure B-11. Regional natural gas consumption comparisons with IEA WEO 2022. IEA-APS = Announced Pledges Scenario, IEA-STEPS = Stated Policies Scenario. Note IEA WEO gas consumption in Australia_NZ is not separated out from rest of Asia.

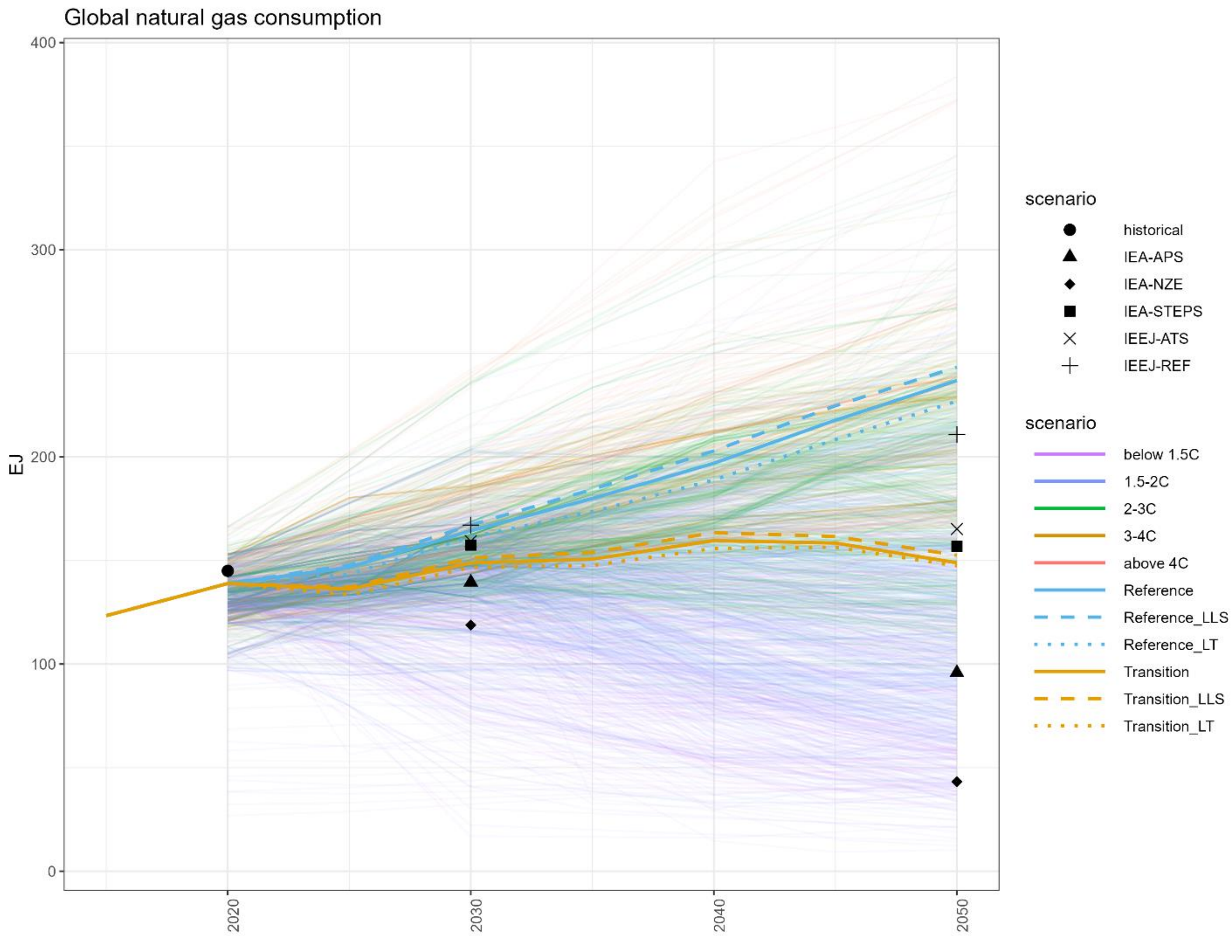


Figure B-12. Global natural gas consumption comparisons with IPCC AR6 scenarios (shown in colored lines corresponding to global mean temperature threshold) and IEA WEO 2022 and Institute of Energy Economics Japan (IEEJ) scenarios (shown in symbols). IEA-APS = Announced Pledges Scenario, IEA-NZE = Net-Zero Emissions by 2050 Scenario, IEA-STEPS = Stated Policies Scenario, IEEJ-ATS = Advanced Technologies Scenario, IEEJ-REF = Reference Scenario.

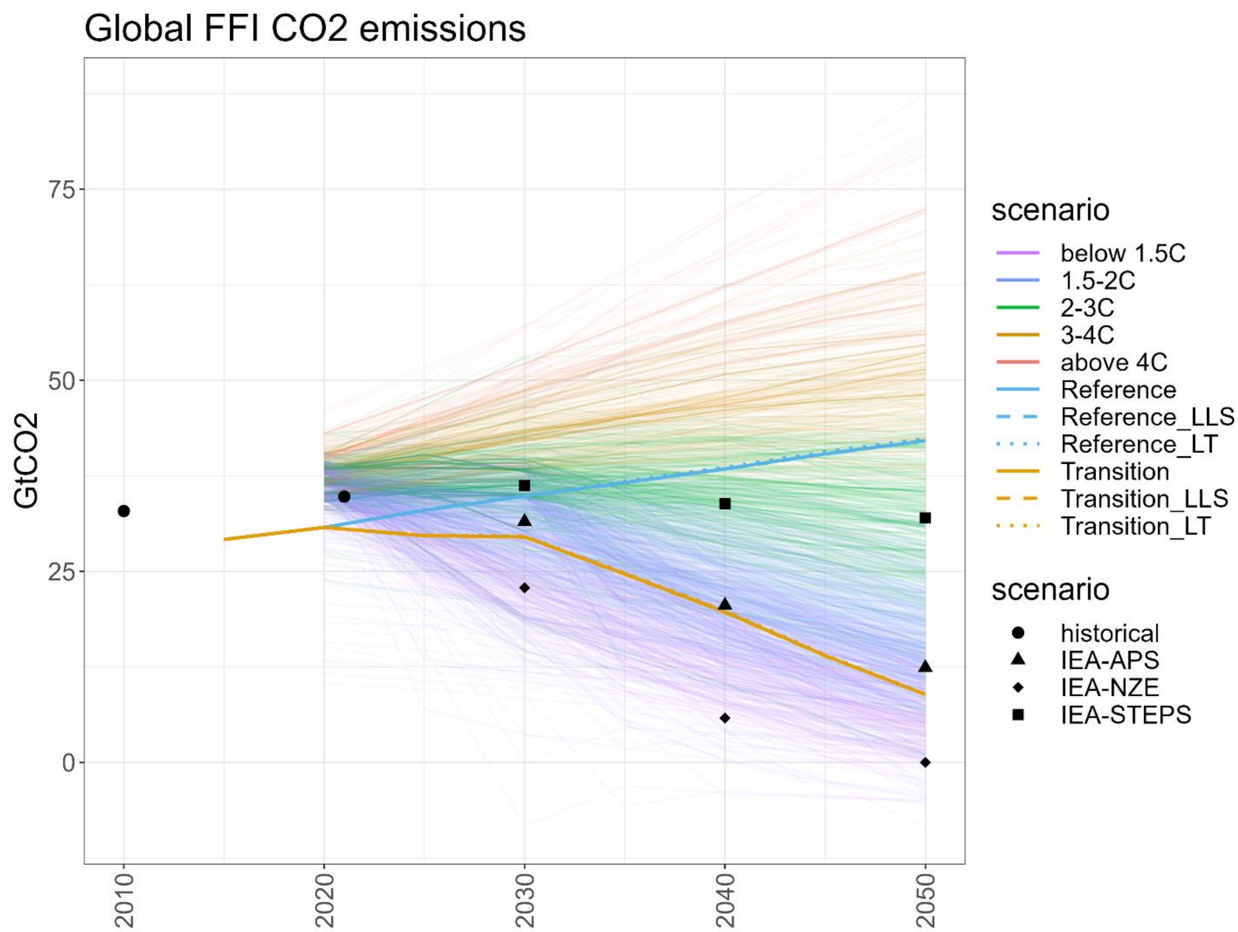


Figure B-13. Global FFI CO2 emissions with IPCC AR6 scenarios (shown in colored lines corresponding to global mean temperature threshold) and IEA WEO 2022 scenarios (shown in symbols). IEA-APS = Announced Pledges Scenario, IEA-NZE = Net-Zero Emissions by 2050 Scenario, IEA-STEPS = Stated Policies Scenario.

Appendix C: Supplementary material for Essay 3

C.1 Literature review

Several methods have been used to analyze the implications of import restrictions on deforestation and LUC emissions. Here, we distinguish between two main groups of methods: impact assessments on deforestation regulation policies **(Table C-1)** and economic modeling studies **(Table C-2).**

Several impact assessments **(Table C-1)** were conducted prior to the enactment of EU deforestation regulations, considering various policy mechanisms. These assessments provide baseline estimates of how much deforestation and LUC emissions could be reduced with EU import restrictions in place. However, they rely on simplified assumptions about how future imports and demand could grow (e.g., using a static annual growth rate based on historical trends[1,2]). These trends might not hold in the future, given changes in socioeconomics, prices, and interactions between different regions' demands. For example, the most recent assessment of EU's deforestation regulations projected an annual growth rate of 1.42% for oil palm imports in EU through 2030 based on historical trends[1]. However, our study finds that EU import demand for oil palm could decline in future years under Reference conditions (**Table C3; see C2.1**). Levels of future import demand could be a key factor in determining how effective import-side restrictions (enacted by specific importer regions) are in reducing deforestation and LUC emissions. Other simplified assumptions assumed in these impact assessments, such as static or historical deforestation intensities, LUC emissions intensities, or yield improvements, could also be limitations in representing future dynamics.

Global economic models that include land-use sector representation or are coupled to a detailed land model offer significant advantages in understanding the implications of changes in policy (e.g., import restrictions on deforestation-linked crops) on deforestation and LUC emissions[3]. Such models represent interactions between agricultural demands, trade, land-use allocation, and resulting LUC emissions. These models can endogenously consider substitution between different markets, agricultural commodities, and land-uses. Several peer reviewed studies **(Table C-2)** used economic models to project changes in trade flows, land-use changes, and LUC emissions. We note that many of these studies used computable general-equilibrium (CGE) models (e.g., GTAP), which offer significant benefit in representing monetary-based trade flows and trade-flows of secondary products (up to the end-use consumer).

In this study, we use a modified version of the Global Change Analysis Model (GCAM) v7, an integrated multi-sectoral model. Using GCAM offers another perspective in understanding the implications of import restrictions on land-use changes and LUC emissions and can be a useful point of comparison with previously used economic models. In contrast to CGE models, GCAM represents commodity trade in terms of physical primary equivalent units, and therefore providing a more direct connection of trade flows to land use. Furthermore, while many CGE-models represent implications of import restrictions in a historical counterfactual context, GCAM simulates them in a forward-looking context. Thus, using GCAM can help fill an important gap in understanding future land and economic implications of import restriction policies.

Study	Commodity	Policy region	Producing region	Study period	Methodology/Assumptions	Metrics evaluated
Bougas et al. (2023)[1]	All commodities covered in EU's deforestation regulation: Palm oil, cattle (beef), cocoa, coffee, soy, and wood products	EU	Global	2009-2019 (historical analysis) and projections to 2030	1. Uses import data as proxy for consumption 2. Uses static annual growth rate for EU commodity demand 3. Uses static deforestation (ha/tonne) and emissions (tCO2/tonne) intensity of imports 4. Leakage not considered	1. Land use changes 2. LUC emissions
IDH (2020)[2]	Palm oil and soy	12 countries in EU	Global	2018-2030	1. Uses static annual growth rates for EU commodity demand and sustainably sourced share 2. Estimates land needed to satisfy future demand, with country-specific (historical trend) yield improvements 3. Uses static emissions intensity of imports 4. Leakage not considered	1. Land use changes 2. LUC emissions
Heflich (2018)[4]	Beef, soy, palm oil, maize, sugar, rapeseed	EU	Global	1970-2016 (historical analysis) and projections to 2030	1. Estimates import price increases due to regulations and use E3ME model to project annual growth rates for each commodity through 2030 2. Uses static share of EU imports in total consumption 3, Uses static deforestation and emissions intensity 4. Leakage not considered	1. Land use changes 2. LUC emissions 3. EU GDP and employment
COWI (2018)[5]	Meat/beef maize/corn,	EU, UK	Global	2015-2030	1. Uses simple demand growth rate projections and land use assumptions for commodities and regions to estimate additional land use requirements and deforestation 2. Leakage not considered	1. Land use changes

Cuypers et al. (2013)[6]	Several (meat and non-meat), services, textiles, wood products, manufacturing, energy, chemicals, mining, and transport	EU, UK	Global	1990-2008 (historical analysis) and projections to 2030	1. Uses LANDFLOW (a physical-units trade model) and GTAP-MRIO (a monetary value trade model) to assess global trade flows of agricultural and forest commodities with embodied deforestation historically 2, Makes demand projection assumptions to 2020 and 2030 (e.g., based on diet changes, bioenergy plans) 3. Leakage not considered	1. Trade flows [physical] and [$] 2. Land use changes

Table C-1. Summary of previous EU deforestation impact assessments**.** Table adapted from Table 7.15 from Bougas et al. (2023), with details added.

Study	**Model**	**Commodity**	**Policy region**	**Producing region**	**Study period**	**Scenarios**	**Metrics evaluated**
Villoria et al. (2022)[7]	GTAP-AEZ	Soybean	EU, China	Brazil (spatially explicit, and with market shares of each company), displacement to Bolivia, Argentina, Paraguay	2011-2016 (**Historical counterfactual**)	1. Amazon Soy Moratorium (voluntary zero-deforestation commitment by companies) 2. ASM + pledged, yet to be implemented, global voluntary zero deforestation commitments in Brazil's soy supply chain 3. Adoption of zero-deforestation by all companies export to EU 4. Zero-deforestation by all companies export to China 5. (3) + (4)	1. Trade flows [$] 2. Land use change 3. LUC GHG emissions

Busch et al. (2022)[8]	GTAP-BIO and OSIRIS	Palm	EU, China, US, global	Indonesia (spatially explicit: high vs. low deforestation)	2000-2015 (**Historical counterfactual**)	1. Base scenario (all Indonesian palm oil treated equally, single global price) 2. Primary policy scenario: Europe imposed ban on high-deforestation palm oil 3. Secondary policy scenarios: expand ban to EU + US, EU + US + China, all other countries outside Indonesia and Malaysia	1. Trade flows [$] 2. Prices 3. Land use change 4. LUC GHG emissions 5. Equivalent carbon prices
Taheripour et al. (2019)[9]	GTAP-BIO	Palm	domestic (Malaysia and Indonesia), global	Malaysia and Indonesia	2011-2016 (**Historical counterfactual**)	1. Regulation policy that freezes production of oil palm in M&I at 2011 levels via domestic production tax 2. (1) + an economic incentive (subsidy) to freeze forest area in M&I at 2011 level 3. Uniform international tariff on the world imports of palm oil that freezes production of oil palm in M&I at 2011 levels along with freeze in forest area in M&I	Environmental metrics: 1. Land use change 2. LUC GHG emissions Economic metrics: 1. Consumer price index of vegetable oil 2. Wage rate 3. Welfare Climate mitigation metrics: 1. Cost of abatement
Leijten et al. (2023)[10]	GTAP-AEZ	Palm	global	global	2014-2030	1. Business as usual (BAU) 2. **Full implementation of ZDCs** globally, across sectors	1. Land use changes

Delzeit et al. (2021)[11]	DART-BIO	Palm oil biofuel	EU	global	2011-2030	1. Reference: no biofuel policies from 2019 onwards 2. Minimum of 2018 biofuel consumption shares; Palm oil biodiesel reduced to 0% between 2022 and 2030 3. 7% of total consumption in transport until 2030; Palm oil biodiesel reduced to 0% between 2022 and 2030 4. 7% of total consumption in transport until 2030; No restriction on palm oil biodiesel	1. Ag commodity production and consumption, trade flows, and prices ($) 2. Land use change
Valin et al. (2015)[12]	GLOBIOM	Palm oil biofuel	EU	global	2010-2030	1. Reference: biofuel consumption in EU (3.2%) and globally 2. Feedstock scenarios 3. Policy scenarios: a. EU biofuel mix in 2020 b. EU biofuel mix in 2020 with 7% cap 4. Explorative scenarios, including lower/higher deforestation levels	1. Land use changes 2. LUC emissions

Table C-2. Summary of previous global economic modeling studies on deforestation-linked oil crop trade restrictions.

C.2 Methodology and scenario design

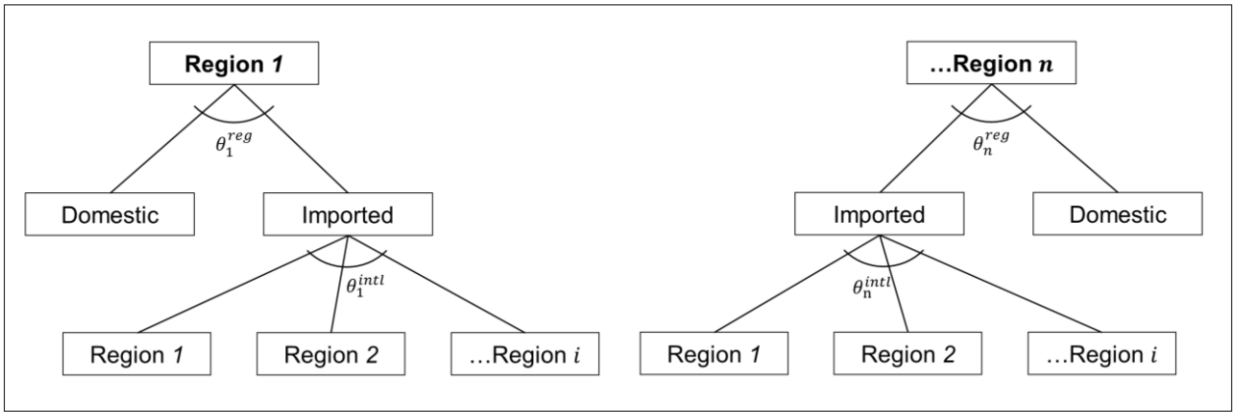


Figure C-1. Logit-based Armington bilateral trade framework. Bilateral trade flows from region *i* to region *n* are observed. Adapted from Fig S3 in Zhao et al. (2022).

Scenario	Policy	Import restricting regions	% share of 2020 import demand represented by the set of import restricting regions		% change in import demand between 2020 and 2050 (in REF scenario) for the set of import restricting regions	
			Palm	Soy	Palm	Soy
REF	None	n/a	0%	0%		
EU freeze	Ceiling on imports from deforesting regions at 2020 levels	EU	20%	18%	-15%	38%
HighInc freeze	Ceiling on imports from deforesting regions at 2020 levels	EU, rest of Europe (EFTA and Europe_Non_EU), Argentina, Australia_NZ, Brazil, Canada, China, Japan, Mexico, Middle East, Russia, South Korea, Taiwan, USA	51%	77%	13%	50%
EU/Top 5 freeze	Ceiling on imports from deforesting regions at 2020 levels	EU and top 5 net importers for oil palm and soy: For oil palm: EU, India, China, Pakistan, Middle East, Australia_NZ For soybean: EU, China, rest of Southeast Asia, Middle East, Africa_Northern, Indonesia	64%	78%	33%	61%
EU ban	Full ban on imports from deforesting regions	EU	20%	18%	-15%	38%

Land protect	Protect forest land in each deforesting region equivalent to land reduced from oil palm and soy production in *HighInc freeze - REF*	n/a		

Table C-3. Scenario design with import demand summary statistics. 'Deforesting regions' are defined as regions deforesting in *REF* between 2015 and 2050 (see **Figure C-3** for details). % values are calculated on the basis of palm and soy import demand volumes (Mt).

C.2.1 Reference scenario

Our baseline *REF* scenario is consistent with limiting warming to 2°C by 2100. This scenario includes emission constraints on FFI emissions for each GCAM region, consistent with "NDC++" pathways in Iyer et al. (2022). Further, we included a global bioenergy constraint, limiting 1st and 2nd generation bioenergy to less than 33.4 EJ in 2020, increasing linearly to 41.7 EJ in 2030, 58.4 EJ in 2050, and 100 EJ in 2100.

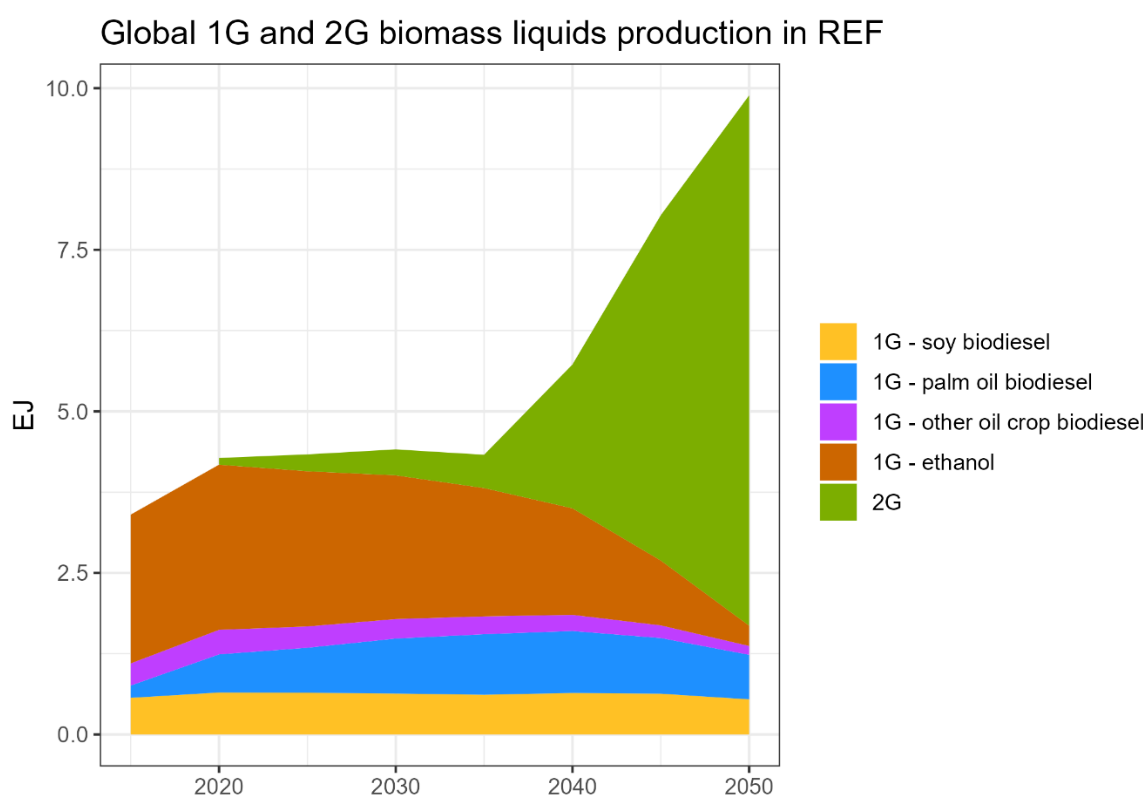


Figure C-2. Global 1G and 2G biomass liquids production in *REF* scenario.

The trajectory of first- versus second-generation liquid biofuels in our *REF* scenario **(Figure C-2)** has important implications for near-term versus longer-term (i.e., 2030 versus

2050) in our results (see discussion in section S3 below). Changes in production of first-generation biodiesel from oil crops (soy, palm oil, or other oil crops) are minimal over the coming decades, with small declines in 2050 relative to 2020 levels. In contrast, production of second-generation liquid biofuels grows significantly from 2035 onward.

Uncertainty in *REF* scenario biofuel levels could have important implications for our results in import restriction scenarios. If growth of second-generation biofuels is lower than projected here, there would be higher levels of first-generation biofuels in the *REF* scenario, and consequently, larger magnitudes of change (in oil crop trade flows) and higher effectiveness in reducing deforestation and LUC emissions under import restriction scenarios. Given the high rates of land-switching leakage under import restriction scenarios observed in our results (see 4.3.2 *'Land-use and emissions implication of import restrictions'* section), another key area of uncertainty in our *REF* baseline relates to land-switching logit parameters. If these parameters were tuned to maintain more rigidity in land use allocation, land-switching leakage rates might be lower, resulting in higher effectiveness in reducing deforestation and LUC emissions under import restriction scenarios. Several potential sources of uncertainty in the *REF* scenario could affect the exact magnitudes observed in our results, but we believe that the trends would still hold.

C.2.2 Import restriction scenarios

The import restriction scenarios were modeled by including import constraints between source and destination markets for oil palm and soybean trade. Restricted export markets were defined as regions deforesting between 2015-2050 in the *REF* scenario (**Figure C-3).**

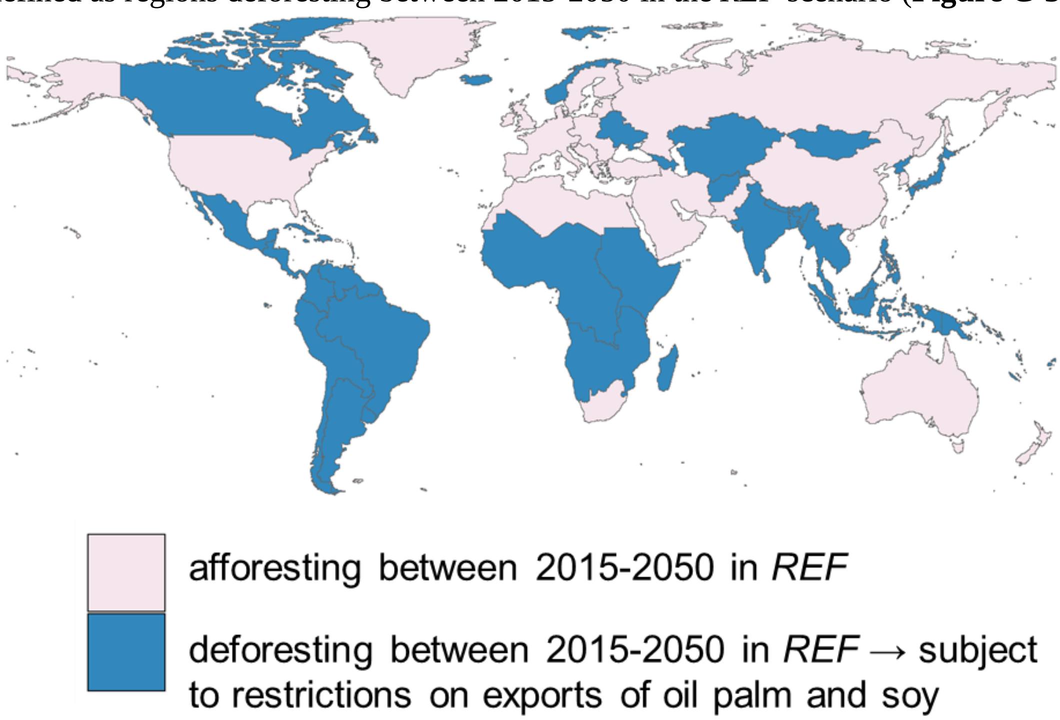


Figure C-3. Restricted export market regions under import restriction scenarios (shown in blue). These regions are defined as those GCAM regions that had net deforestation between 2015 and 2050 in the *REF* scenario. These regions are: Africa_Eastern, Africa_Southern, Africa_Western, Argentina, Brazil, Canada, Central America and Caribbean, Central Asia, Colombia, Europe_Eastern, European Free Trade Association, India, Indonesia, Japan, Mexico, South America_Northern, South America_Southern, South Asia, rest of Southeast Asia

C.2.3 Land protect scenario

The *Land Protect* scenario is intended to be a policy of comparable magnitude to the *HighInc freeze* scenario. This scenario was modeled by calculating the reduction in oil palm or soybean land in each deforesting (export-restricted) region under the *HighInc freeze* scenario. This value was added to forest land value in the *REF* scenario in each region to form a set of explicit land protection constraints for each deforesting region from 2025 to 2050.

In comparing the cumulative economic impact changes **(Figure 4-4)** under import restriction scenarios and the *Land Protect* scenario, we note that economic impacts on agricultural producers and consumers are just one aspect of the economic costs of each policy. Direct land protection policies could have other economic costs, such as those related to measurement, reporting, and verification (MRV). A full comparison of the costs of import restriction policies versus direct forest protection policies is outside the scope of this study. However, we note that import restrictions (as currently structured in the EU), which rely on deforestation-free certification of specific commodity supply chains (from specific regions) in order to allow imports could also face issues with MRV comparable to those of direct land protection policies.

C.2.4 Leakage rate calculations

We calculate rates of leakage occurring for each deforestation-linked oil crop producing region in early (land-switching leakage) and end (market-switching) stages of the supply chain. In the paper results, leakage rates are calculated for the year 2050.

Market-switching leakage

The market-switching leakage rate represents the extent to which reductions in oil crop (oil palm or soybean) production in deforestation-linked regions due to import restrictions are offset by increases in oil crop production for other markets. For an oil crop producing region, p, the total "net" oil crop supply change, $\Delta Q_{p,s}^{Net}$, between a scenario (s) and the *REF* scenario can be calculated as the sum of changes in the bilateral supply flows ($Q_{p,r,s}$) across all the bilateral destinations (r), see Eq. (1).

$$\Delta Q_{p,s}^{Net} = \sum_r \left(Q_{p,r,s} - Q_{p,r,REF}\right) \qquad (1)$$

When only accounting for the destinations that imposing import restrictions, the total "gross" oil crop supply change, $\Delta Q_{p,s}^{Gross}$, is calculated in Eq. (2):

$$\Delta Q_{p,s}^{Gross} = \sum_{p,r}\left[\left(Q_{p,r,s} - Q_{p,r,REF}\right) \cdot I\left(Q_{p,r,s} - Q_{p,r,REF} < 0\right)\right] \quad (2)$$

whereas the indicator function, $I(\cdot)$, takes the value of 1 if $Q_{p,r,s} - Q_{p,r,REF} < 0$ and 0 otherwise. Thus, the market-switching leakage rate, $\gamma_{p,s}^{Market-switching}$, for deforestation-linked oil crop producer region p, under scenario s, can be calculated as:

$$\gamma_{p,s}^{Market-switching} = \left(1 - \frac{\Delta Q_{p,s}^{Net}}{\Delta Q_{p,s}^{Gross}}\right) \cdot 100\% \quad (3)$$

Most of the trade reduction due to import restrictions is absorbed by other destinations if $\gamma_{p,s}^{Market-switching}$ is closer to 100%, and most of the trade reduction is absorbed by production if $\gamma_{p,s}^{Market-switching}$ is closer to 0%.

Land-switching leakage

The land-switching leakage rate represents the extent to which reductions in oil crop (oil palm or soybean) land allocation in deforestation-linked regions due to import restrictions are substituted with non-forest land allocation. The land-switching leakage rate for deforestation-linked producer regions, under scenario s, can be calculated as:

$$\gamma_{p,s}^{Land-switching} = \left(1 - \frac{\left|L_{p,s}^{Forest} - L_{p,REF}^{Forest}\right|}{\left|L_{p,s}^{Oil\ crop} - L_{p,REF}^{Oil\ crop}\right|}\right) \cdot 100\% \quad (4)$$

Whereas $L_{p,s}^{Forest}$ and $L_{p,s}^{Oil\ crop}$ represent the land allocation in region p and scenario s for forest and oil crop, respectively. When $\gamma_{p,s}^{Land-switching}$ is closer to 100%, reductions in oil crop land are absorbed by other (non-forest) land uses. When $\gamma_{p,s}^{Land-switching}$ is closer to 0%, reductions in oil crop land encourages higher afforestation.

C.3 Additional results (figures and tables)

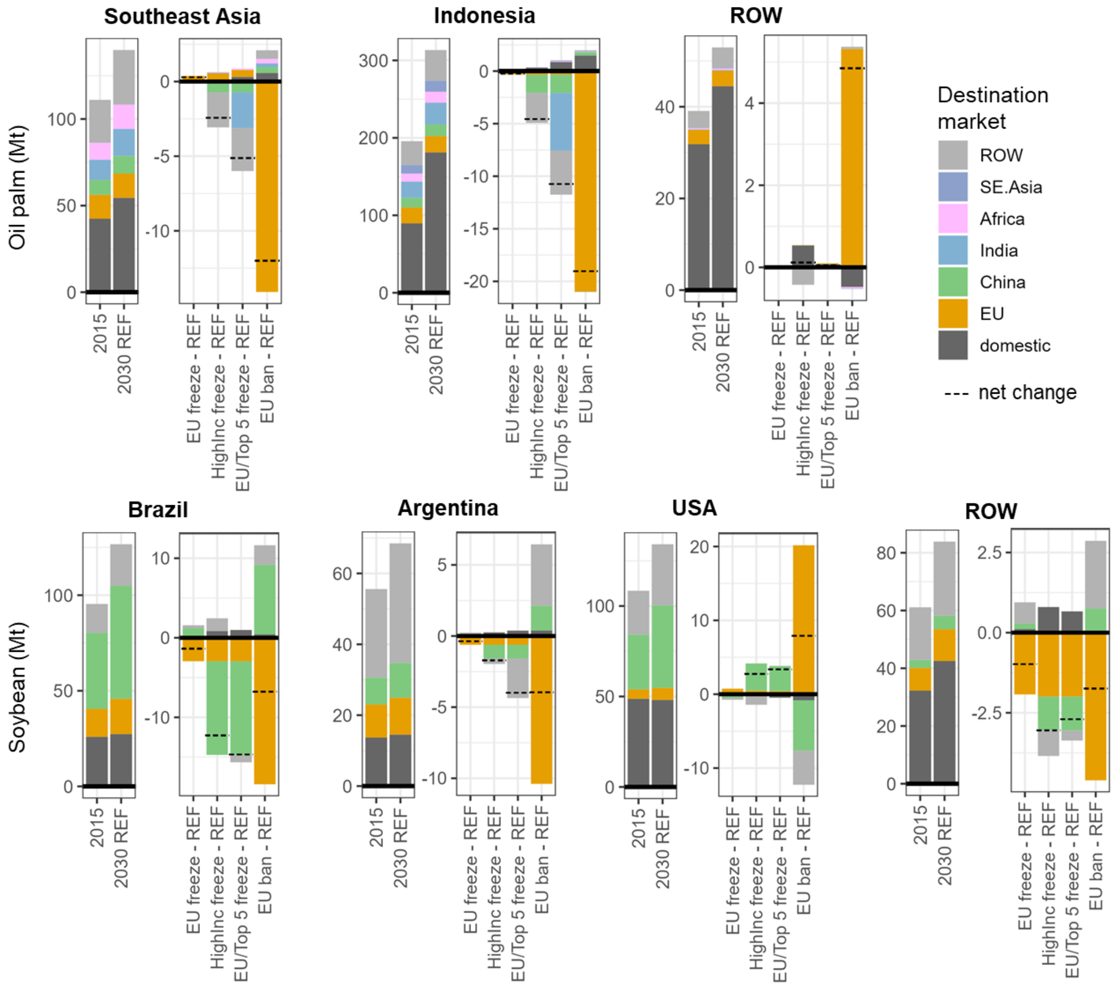


Figure C-4. Oil palm and soybean production (domestic and bilaterally traded flows). Top) oil palm and bottom) soybean production volumes by region across scenarios (million tons). The left panel for each region shows total production in 2015 and 2030 *REF* and the right panel for each region shows the change in production between each import restriction scenario and *REF* in 2030. Domestic production volumes are consumed within the indicated producing region.

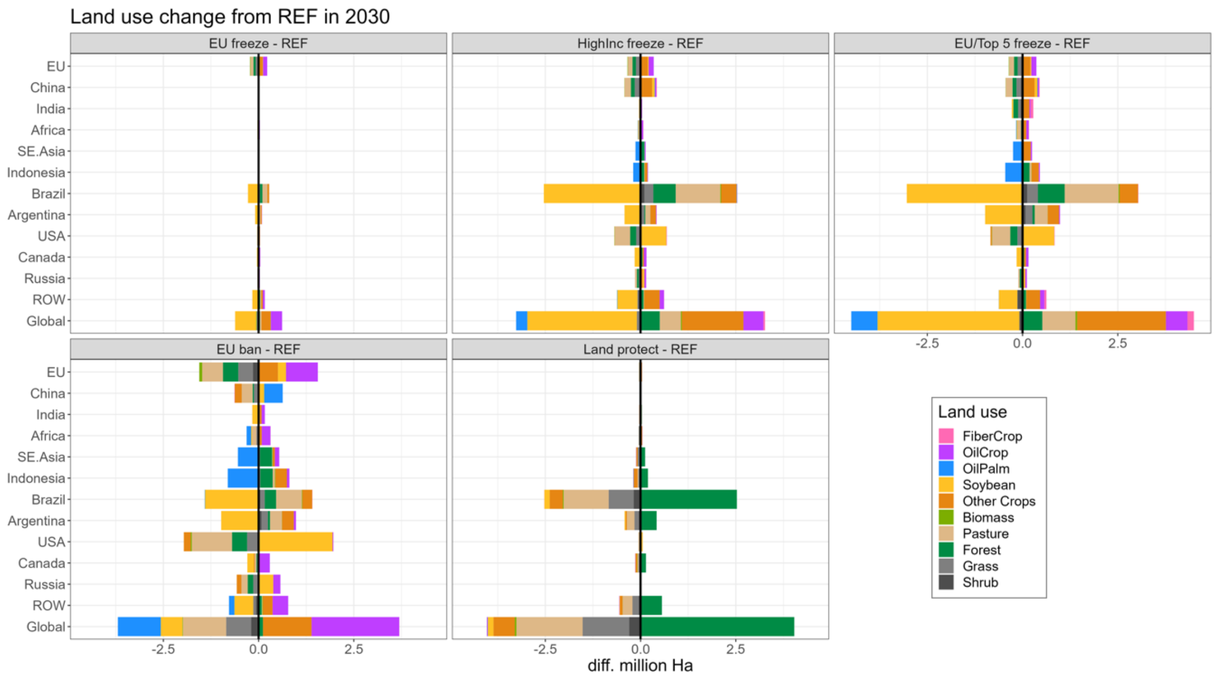


Figure C-5. Land use change. The panels show changes in land use across scenarios relative to *REF* in 2030 (million ha).

In the near term (2030), the EU substitutes other oil crops (e.g., rapeseed and sunflower oils) to meet biofuel demands, grown domestically or imported from other regions, particularly in the *EU ban* case in which there is a total phaseout of palm and soybean imports from deforesting regions **(Figure S3)**. By 2050, land substituted for other oil crops is greatly reduced as the use of all first-generation biofuels in the EU is reduced in the baseline *REF* scenario **(Figure 2)**.

a. Cumulative 2025-2050	EU freeze	HighInc freeze	EU/Top 5 freeze	EU ban	Land protect
Indonesia	+0.03%	-0.5%	-0.9%	-1.2%	-1.2%
RO SEAsia	+0.06%	-1.5%	-0.4%	-1.9%	-1.6%
Brazil	-0.6%	-5.1%	-6.7%	-1.4%	-9.1%
Argentina	-0.04%	-0.9%	-3.8%	-2.3%	-3.6%
Global	-0.04%	-0.5%	-0.6%	0.00%	-1.9%
b. Cumulative 2025-2075	**EU freeze**	**HighInc freeze**	**EU/Top 5 freeze**	**EU ban**	**Land protect**
Indonesia	+0.02%	-0.5%	-1.1%	-1.1%	-1.3%
RO SEAsia	+0.04%	-1.8%	-1.0%	-1.7%	-1.8%
Brazil	-0.6%	-5.4%	-7.2%	-1.5%	-9.7%
Argentina	0.00%	-0.8%	-3.7%	-2.2%	-3.8%
Global	-0.04%	-0.5%	-0.7%	+0.05%	-2.1%
c. Cumulative 2025-2100	**EU freeze**	**HighInc freeze**	**EU/Top 5 freeze**	**EU ban**	**Land protect**
Indonesia	+0.02%	-0.5%	-1.2%	-1.1%	-1.3%
RO SEAsia	+0.04%	-1.9%	-1.1%	-1.7%	-1.9%
Brazil	-0.6%	-5.4%	-7.2%	-1.5%	-9.8%
Argentina	0.00%	-0.8%	-3.7%	-2.2%	-3.9%
Global	-0.03%	-0.5%	-0.7%	+0.07%	-2.1%

Table C-4. Cumulative LUC emissions changes. Percent change in cumulative LUC emissions (a) 2025-2050, (b) 2025-2075, (c) 2025-2100) in key deforestation-prone oil crop exporting regions and globally compared to *REF***.**

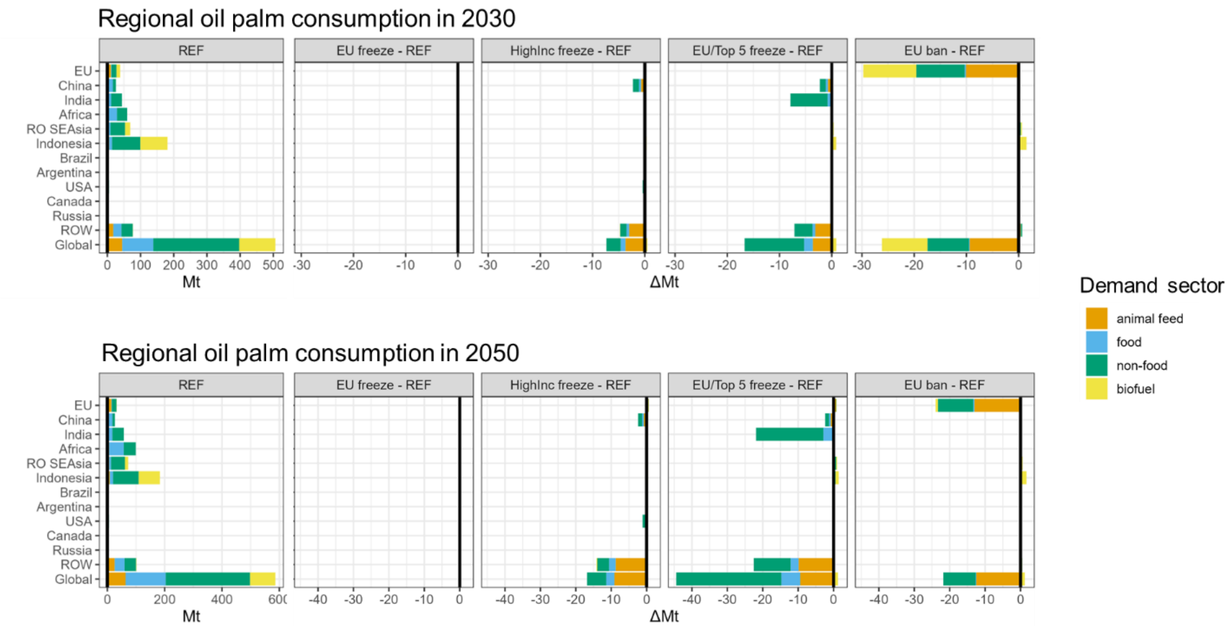


Figure C-6. Regional oil palm consumption. The leftmost panels show *REF* oil palm consumption in 2030 (top) and 2050 (bottom) across demand sectors: animal feed, food, non-food, and biofuel. The right panels show changes in oil palm consumption relative to *REF* in 2030 (top) and 2050 (bottom). Units are in million tons (Mt).

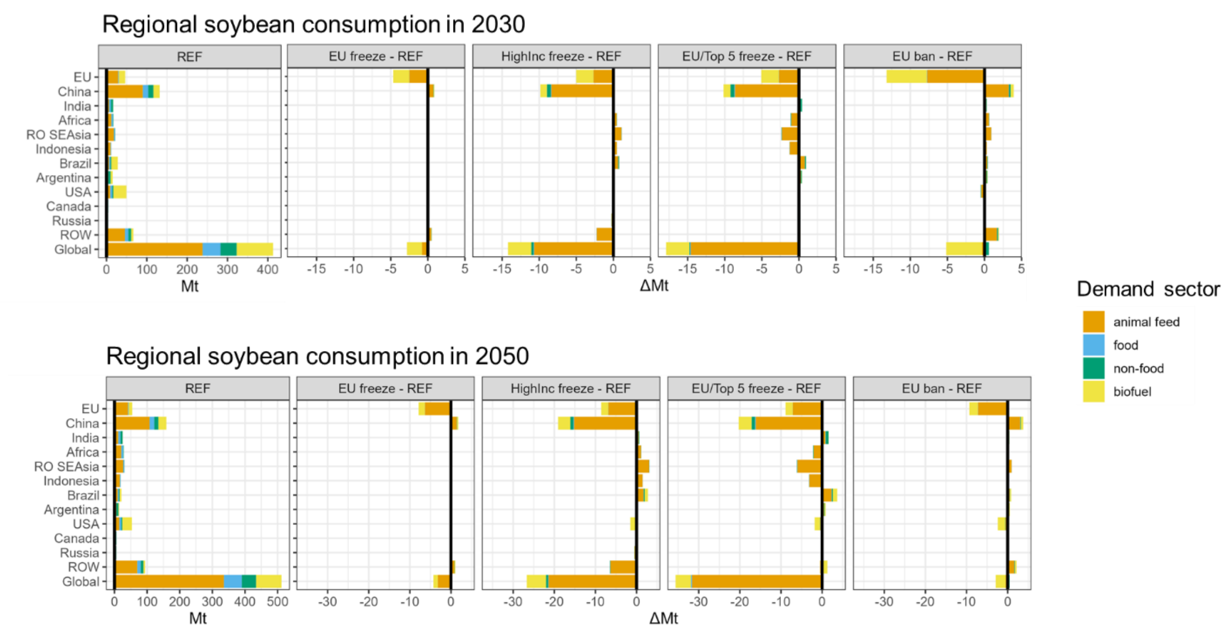


Figure C-7. Regional soybean consumption. The leftmost panels show *REF* soybean consumption in 2030 (top) and 2050 (bottom) across demand sectors: animal feed, food, non-food, and biofuel. The right panels show changes in soybean consumption relative to *REF* in 2030 (top) and 2050 (bottom). Units are in million tons (Mt).

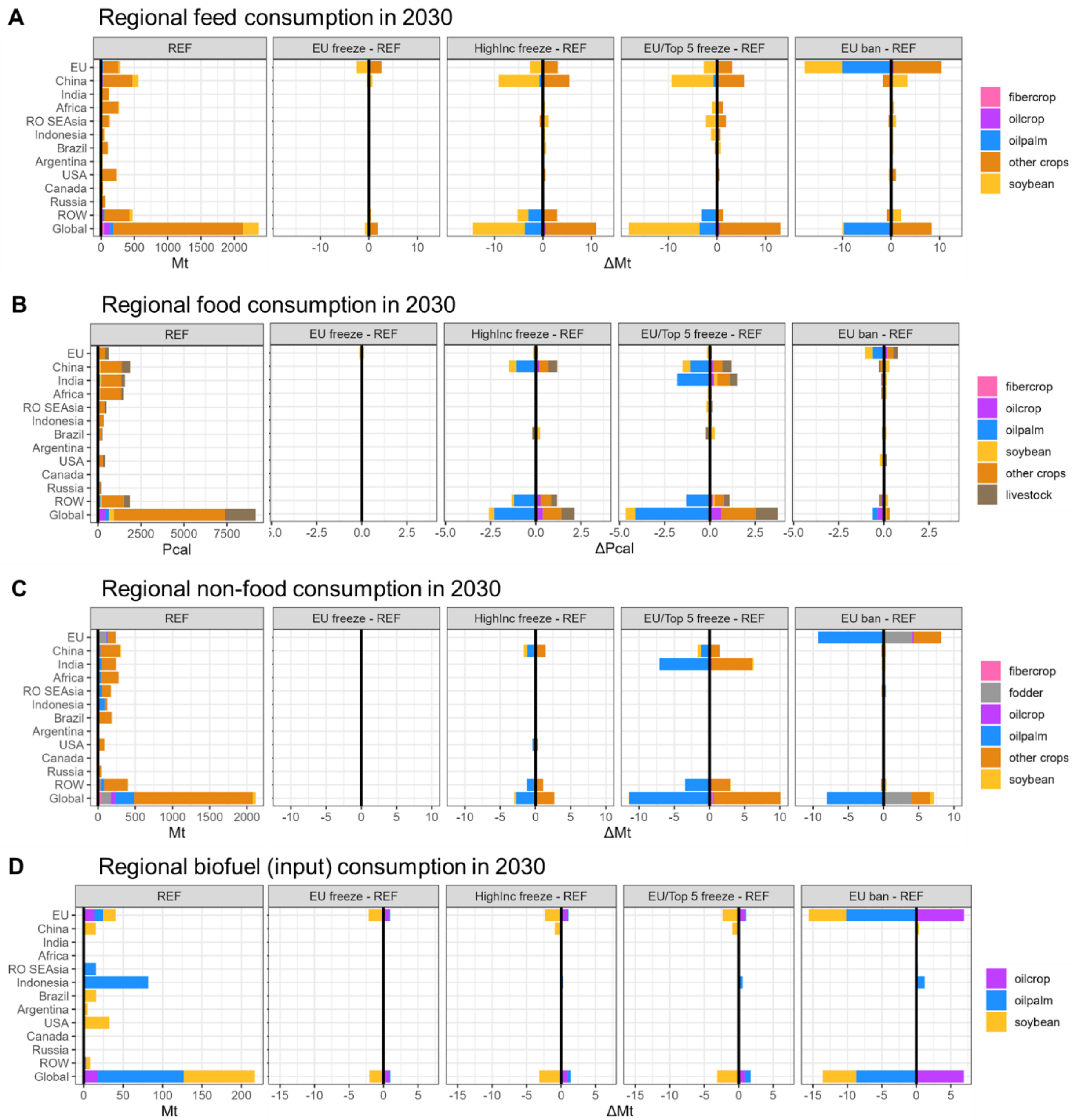


Figure C-8. Regional agricultural consumption by demand sector in 2030. A) animal feed (Mt), B) food (Pcal), C) Non-food, D) biofuel input (Mt). The leftmost panels show *REF* consumption of agricultural commodities. The right panels show changes in agricultural consumption relative to *REF*.

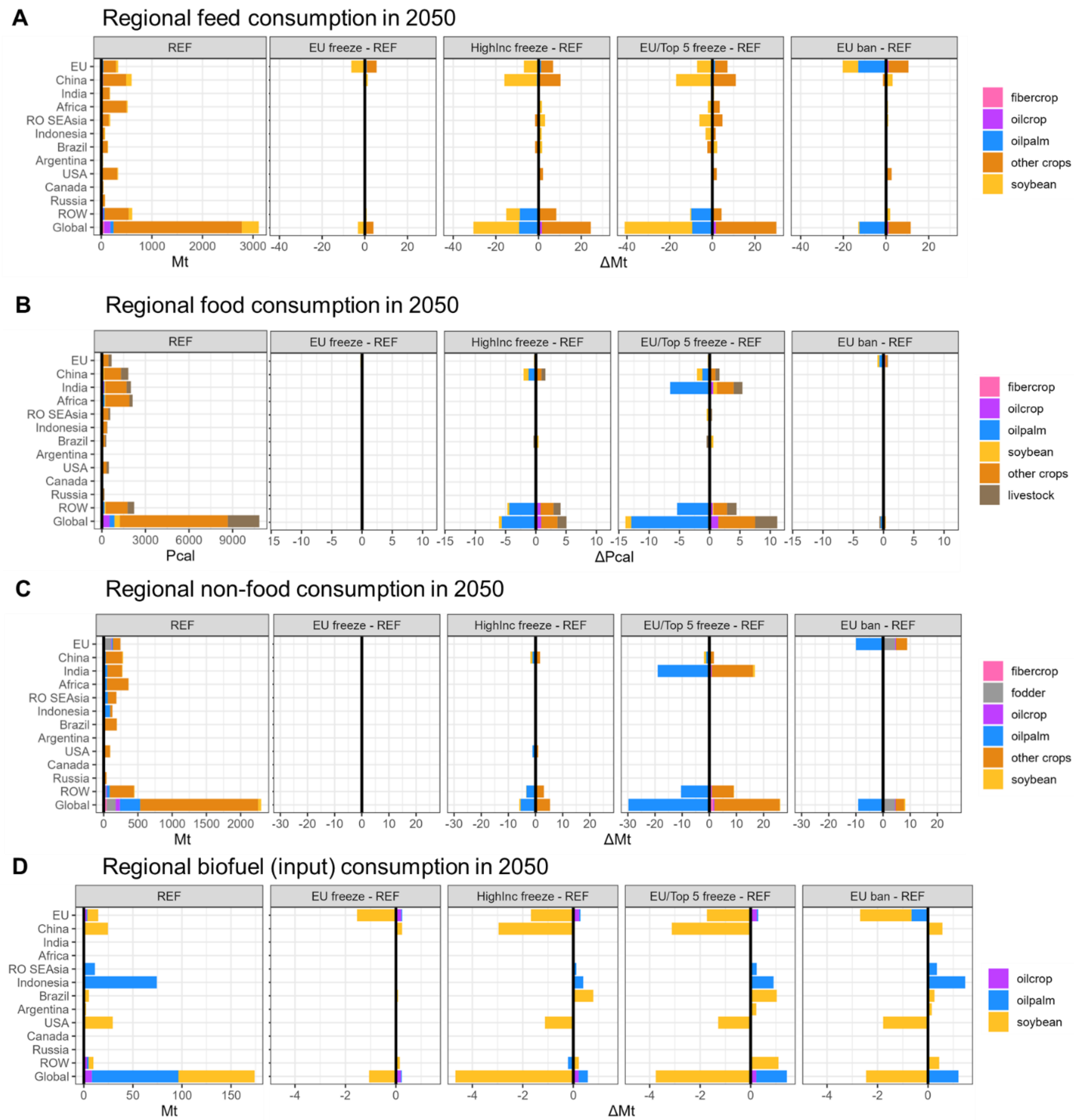


Figure C-9. Regional agricultural consumption by demand sector in 2050. A) animal feed (Mt), B) food (Pcal), C) Non-food, D) biofuel input (Mt). The leftmost panels show *REF* consumption of agricultural commodities. The right panels show changes in agricultural consumption relative to *REF*.

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Chapter 1

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Chapter 2

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